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A DRY DEPOSITION MODULE FOR REGIONAL ACID DEPOSITION

by

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Methods to compute surface dry deposition velocities for sulfur dioxide, sulfate, ozone, NO plus NO_2, and nitric acid vapor over much of the North American continent have been developed for use with atmospheric numerical models of long-range transport and deposition. The resulting dry deposition module, actually a FORTRAN subroutine and a landuse map, has been designed for use with Eulerian models but can also produce maps and averages of deposition velocities for other types of models. The module provides much of the data required to compute deposition velocities: a computerized landuse map, surface roughnesses keyed to landuse type and season, and similarly keyed surface resistances of pollutant uptake. The landuse map has basic grid cells with dimension of 1/4 deg longitude by 1/6 deg latitude, over the region from 52 to 134 deg west longitude and 24 to 55 deg north latitude. External input data must specify geographical location, season, and height at which deposition velocity estimates are to be made, as well as provide values of atmospheric parameters such as solar irradiation, wind speed, atmsopheric stability, and boundary-layer mixing height. These parameters are usually average values for gridded areas defined by the Eulerian model. A fairly general dry deposition module has been produced as well as a module adapted specifically for the Regional Acid Deposition Model being developed at the National Center for Atmospheric Research.

CONTENTS

Abstract..... iii

Tables..... vi

Figures..... vii

Acknowledgements..... viii

Section

1. Introduction..... 1

2. Procedures for Calculating Deposition Velocities..... 2

Basic equations..... 3

Spatial averaging..... 7

3. Surface Resistance..... 13

4. Module Application..... 23

Landuse data..... 23

Computer code for general applications..... 23

NCAR dry deposition module..... 27

5. Conclusion..... 36

References 38

Appendix 1. 43

Appendix 2. 52

TABLES

Number		Page
1	Surface roughnesses (cm).....	5
2	Summary of results from selected investigations on dry deposition for SO_2, O_3, NO_x, NO_2, and HNO_3. Measurement methods include those indicated by GD for gradient and EC for eddy correlation.....	16
3	Surface resistances (s cm^{-1}) for sulfur dioxide for various landuse types and insolation categories.....	18
4	Surface resistances (s cm^{-1}) for ozone for various landuse types and insolation categories.....	19
5	Maximum deposition velocities (cm s^{-1}) for particulate sulfate.....	21

FIGURES

Number		Page
1	A landuse map of North America with dominant landuse types represented by alphanumeric symbols: 1 (urban land), 2 (agriculture land), 3 (range land), 4 (deciduous forest), 5 (coniferous forest), 6 (mixed forest including wetland), 7 (water), 8 (barren land), 9 (non-forested wetland), A (mixed agricultural and range land), and B (rocky open area occupied by low growing shrubs).....	24
2	Flow chart for ANL dry deposition module.....	25
3	A dry deposition velocity map of SO_2 for summer daytime conditions. The integers (0,1,---, and 9) in the map represent deposition velocities with intervals of 0.117 cm s^{-1}; e.g., 0 and 1 represent the ranges of deposition velocities 0 to 0.117 and 0.117 to 0.234 cm s^{-1}, respectively.....	28
4	A deposition velocity map for $SO_4^=$, as in Figure 3 except with deposition velocity intervals of 0.0412 cm s^{-1}.....	29
5	A deposition velocity map for O_3, as in Figure 3 except with deposition velocity intervals of 0.113 cm s^{-1}.....	30
6	A deposition velocity map for NO_x, as in Figure 3 except with deposition velocity intervals of 0.0751 cm s^{-1}.....	31
7	A deposition velocity map for HNO_3, as in Figure 3 except with deposition velocity intervals of 0.596 cm s^{-1}.....	32
8	Flow chart for NCAR dry depositon module.....	33

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SECTION 1

INTRODUCTION

Widespread interest in sulfur and acid deposition has stimulated development of many numerical models for simulating long-range transport and deposition of various pollutants (e.g., Bolin and Persson, 1975; Sheih, 1977; Liu et al., 1982). Such efforts in the United States are important in assessing the effects of acid deposition and developing alternative control strategies, in work for the National Acid Preciptation Assessment Program (NAPAP). These needs have been the impetus for large efforts in acid rain research (e.g., Caton et al., 1984), including the development of the Regional Acid Deposition Model (RADM) by the National Center for Atmospheric Research (NCAR, 1985).

One of the most important processes treated in these models is surface dry deposition, where rates of deposition are obtained by multiplying pollutant concentrations by deposition velocities. For a number of reasons, use of deposition velocities in such modeling efforts has been inadequate at times. To improve estimation of the deposition velocities, Sheih et al. (1979) compiled the existing formulae and necessary data for the continental United States and its surrounding regions. The resulting dry deposition module, a FORTRAN subroutine, has been adapted for use with several models (e.g., Endlich et al., 1984). In the present report, the earlier work is modified to incorporate considerable new research findings acquired during the last several years. In addition to sulfur dixode and sulfate particles addressed in the earlier report, ozone, NO plus NO_2, and HNO_3 are included in the revised module described here. Further, the use of input data to the module has been altered to conform with those provided by modern, sophisticated Eulerian models, particularly RADM.

A large number of variables control the dry deposition velocities of airborne chemical substances. Each chemical species has distinct chemical and physical properties that strongly affect uptake at the surface. Correspondingly, each type of surface has its own influential set of physical, chemical, and biological characteristics. Indeed, deposition velocities vary widely depending on chemical species, surface type, season, and time of day. For a region as large as the contiguous United States and surrounding areas in Canada, Mexico, and bordering seas, development of an appropriate dry deposition module requires some balance between identification of the details of processes that control dry deposition and the computational time available to estimate deposition velocities over large areas in small time steps. In the present study, we address a simplified scheme to compute dry deposition velocities averaged over surface grids with typical side dimensions of tens of kilometers. Considerable generalization of results from research on dry deposition is made in order to achieve a working dry depositon module.

SECTION 2

PROCEDURES FOR CALCULATING DEPOSIITON VELOCITIES

BASIC EQUATIONS

The deposition velocity v_g for a gas at height z over aerodynamically rough surfaces is computed from the equation given by Wesely and Hicks (1977) as

$$v_g = ku_*[\ln(z/z_o) + 2(D_h/D_g)^{2/3} + ku_*r_g - \psi_c]^{-1}, \quad (1)$$

where k is the von Karman constant, u_* is the friction velocity, z_o is the aerodynamic surface roughness length, D_h and D_g are the molecular diffusivities for heat and the gas of interest, respectively, ψ_c is the stability correction function for trace gases, and r_g is the surface resistance to the uptake of a gas. It can be seen that v_g actually consists of the inverse of the sum of three familiar resistances: $r_a = [\ln(z/z_o) - \psi_c]/ku_*$ is the aerodynamic resistance, $r_b = 2(D_h/D_g)^{2/3}/ku_*$ is the quasilaminar sublayer resistance, and r_g is surface resistance often written as "r_c" or "r_s" (Wesely and Hicks, 1977). The deposition velocity of sulfate particles over all surfaces is computed as

$$v_p = ku_*[\ln(z/z_o) + ku_*r_p - \psi_c]^{-1}, \quad (2)$$

where r_p is the surface resistance for particle uptake. In this case, $r_p = r_b + r_c$ is the sum of sublayer and surface resistances.

To apply the above equations for deposition velocities, the parameters to be specified are surface roughness, molecular diffusivity, stability correction function for (scalar) trace substances, friction velocity, and surface resistance. All are discussed in this Section except surface resistances r_g and r_p, which are addressed in Section 3.

Values of surface roughness used in the dry deposition module are given in Table 1, and depend only on the landuse type and season. The landuse types are:

1. urban land,
2. agricultural land,
3. range land,
4. deciduous forest,
5. coniferous forest,
6. mixed forest including wetland,
7. water,
8. barren land,
9. non-forested wetland,
10. mixed agricultural and range land, and
11. rocky open areas occupied by low growing shrubs.

The classifications chosen to represent seasons are:

1. midsummer,
2. autumn,
3. late autumn,
4. winter, and
5. transitional spring.

The five seasonal categories are not climatological or calendar seasons in the usual sense, but are indicators of surface conditions that typically occur in the Midwest and noncoastal areas of the Northeast. The first seasonal surface condition, midsummer, indicates that vegetation is lush and healthy. Condition 2 corresponds to traditional autumn conditions in the Northeast, when killing frosts have occurred but most agricultural crops have not been harvested; standing canopies of broadleaf plants and warm season grasses have very limited photosynthetic activity. Condition 3 represents cases where freezing conditions are common, deciduous trees are leafless, field crops have been harvested to expose much bare soil, grass surfaces are brown, and no snow is present. This corresponds to late autumn, early spring, and winter in the Northeast when no snow is present. Condition 4 considers snow-covered surfaces and subfreezing temperatures (except for landuse type 8, for which snow is not considered). Condition 5 addresses surfaces with

TABLE 1. SURFACE ROUGHNESSES (CM)

Landuse	Season				
	1	2	3	4	5
1	300	300	300	300	300
2	25	10	0.5	0.1	3
3	5	5	5	0.1	2
4	100	100	100	100	100
5	100	100	100	100	100
6	100	100	100	100	100
7	*	*	*	*	*
8	0.2	0.2	0.2	0.2	0.2
9	15	10	10	0.1	10
10	10	8	2	0.1	3
11	10	8	6	4	6

* computed from Eq. (3)

emerging green leaves and when small field crops not entirely covering the soil surface. Since no single seasonal surface condition can apply in any given instance to the entire region, care should be taken in determining which condition or combination of conditions is appropriate. For example, Masse and Voldner (1983) adapted the general approach taken here to utilize up to three seasonal categories for one particular time of the year in North America.

The value of roughness over water is computed from the formula given by Hicks and Liss (1976) to provide a smooth transition between aerodynamically smooth and rough flow regimes:

$$z_o = D_a/(9.1u_*) + 0.014u_*^2/g \ , \qquad (3)$$

where D_a is the kinematic viscosity of air and g is gravitational acceleration. For surface Reynolds numbers $R_r = u_* z_o/D_a$ greater than ten, the surface is considered aerodynamically rough and Eq. (1) is appropriate. When R_r has a value less than one, however, the flow is smooth and the value of roughness length scale z_g for gases [implied in Eq. (1) to be equal to $z_o(D_g/D_h)^{2/3}/2$] should be replaced with

$$z_g = D_g/(ku_*) \quad . \tag{4}$$

In this case, Eq. (1) is replaced with

$$v_g = ku_* [\ln(z/z_g) + ku_* r_g - \psi_c]^{-1} \quad , \tag{5}$$

in which the quasilaminar sublayer resistance can be found to be equal to $r_b = [\ln(ku_* z_o/D_g)]/ku_*$. For expediency, we choose to use Eq. (1) when z_o is equal to or greater than 0.1 cm, and Eq. (5) when z_o is smaller. This, rather than use of R_r, as the basis of a criterion for indicating smooth versus rough flow is admittedly inexact, but the effects on estimates of v_g is insignificant, throughout the transition between rough and smooth flow. In the above equations, the molecular diffusivities are estimated from the following:

$$D_a = 0.151 \, [(273 + T)/273]^{1.77}, \tag{6}$$

$$D_g = 0.219 \, [(273 + T)/273]^{1.75} \, (18/m_g)^{1/2} \quad , \tag{7}$$

where m_g is the moleuclar weight of the gas of interest and T is temperature in Celsius.

The friction velocity can be computed as

$$u_* = ku[\ln(z/z_o) - \psi_m]^{-1} \quad , \tag{8}$$

where ψ_m is the stability correction function for momentum.

To evaluate the stability functions, the Monin-Obukhov scale length L can be computed from

$$L = - \rho \, c_p u_*^3 \theta \, /[kg(H + L_w E/14)], \tag{9}$$

where ρ is air density, c_p is the specific heat of air at constant pressure, θ is the potential temperature, H is the sensible heat, and $L_w E$ is the latent heat flux.

The stability functions for stably stratified flow are computed for $0 < z/L < 1$ as:

$$\psi_m = \psi_c = -5z/L \qquad (10)$$

(e.g., Dyer, 1974). For unstable conditions, the following approximation formulae given by Wesely and Hicks (1977) are used, for $0 > z/L > -1$:

$$\psi_m = \exp 0.032 + 0.448 \ln(-z/L) - 0.132 [\ln(-z/L)]^2 \qquad (11)$$

$$\psi_c = \exp 0.598 + 0.390 \ln(-z/L) - 0.090 [\ln(-z/L)]^2 . \qquad (12)$$

SPATIAL AVERAGING

Most Eulerian numerical models of regional or long-range transport and deposition deal with variables averaged over surface grid squares rather than directly with type of surfaces. For example, the mesoscale meteorology model of RADM currently exchanges data with model subcomponents, including the dry deposition module, for grid squares that are 80 km on a side. The average dry deposition velocities for chemical species; computed via Eqs. (1), (2), and (5) can be estimated for each grid cell as follows:

$$v_j = \sum_i^{11} f_i \, v_{ji} , \qquad (13)$$

where f_i is the fraction of land apportioned to each landuse type (i) within the averaging area and v_{ji} is the deposition velocity for each landuse type. Equation (13) is clearly an oversimplification because it, as well as the preceeding equations, ignores the effects of interactions and advection from surface to surface. That is, possible alteration of deposition processes near the edges between different types of surfaces are not taken into account. Although the errors involved might be significant for nonuniform terrain, a scientifically sound, computationally efficient alternative to Eq. (13) has not been found.

The fact that Eulerian models usually deal with grid-averaged variables indicates that the dry deposition module is normally provided with crucial variable such as friction velocity u_*, wind speed u, and that flux H that are grid averages instead of values for each landuse type. For example, variations of u_* in Eqs. (1), (2), and (5) have a strong effect on computed deposition velocities and can be large as a result of different values of z_o for each landuse type are inserted in Eq. (8). Of course, both u and u_* vary locally from surface to surface as variables (such as geostrophic wind speed and Coriolis parameter) external to the planetary boundary layer are held constant. Typically, as a transition is made from a less to more rough surface, u_* increases and $\bar{u}$ decreases in the lower atmosphere. This is corroborated by both experimental and numerical modeling studies (e.g., Hicks and Wesely, 1981). Thus, it is incorrect to assume that either u or u_* is constant close to all surfaces in a grid cell, as was done earlier (Sheih et al., 1979), and might lead to substantial errors in estimating deposition velocities when surface r_g is small (Walcek et al., 1986). Furthermore, as will be seen in Section 3, r_p for sulfate is highly dependent on values of u_* and might be poorly computed if improper estimates of u_* are made.

The approach recommended here is to assume that the product uu_* is constant at a chosen height in the lower 50 m of the atmosphere. This assumption can be shown to be reasonable by application of planetary boundary layer similarity functions (e.g., Fleagle and Businger, 1980; Brutsaert, 1982). For example, uu_* at a height of 15 m is found to be constant within 20% as z_o varies from 0.01 to 100 cm, for fixed, typical values of geostrophic wind speed, latitude, and surface heat flux. Although this approach does not take into account effects such as baroclinicity, nonuniformity surface heat flux within a grid cell, and local nonuniformity of z_o itself, the results do

add to the evidence that the assumption of constant uu_* at heights of 10 to 50 m above a grid cell is reasonable.

To implement the assumption of constant uu_*, we assume that we are given a wind speed $\bar{u}$ and heat flux $\bar{H}$ where the overbar indicates a spatial average over the grid cell. The average $\bar{u}_*$ is computed via Eq. (8) where $\bar{z}_o$ is found as

$$\bar{z}_o = \exp\left(\sum_i^{11} f_i \ln z_{oi}\right), \qquad (14)$$

where z_{oi} is the surface roughness for the i-th landuse type. Then for each landuse type, local u_{*i} is found as

$$u_{*i} = \{k\bar{u}\bar{u}_*/[\ln(z/z_{oi}) - \psi_c]\}^{1/2} \quad . \qquad (15)$$

Equations (14) and (15) produce a self-consistent set of local wind speeds u_i such that the weighted average $\frac{1}{11}\sum_i^{11} f_i u_i^2$ is equal to $\bar{u}^2$ in neutral conditions.

The approach just outlined does not consider local variations of heat flux (or virtual heat flux $H_v = H + L_w E/14$) because the detailed surface information necessary to compute energy budget over each type of surface is not availale. Hence, we assume that the heat and moisture fluxes important in computing the Monin-Obukhov length via Eq. (9) and application via Eqs. (10) to (12) are constant and equal to the grid average. This is a deficiency, but a small one compared to that of assuming constant friction velocity or, alternatively, wind velocity.

The mesoscale meteorology model of RADM currently gives one average profile of wind speed, temperature, and humidity per grid square of 80 km by

80 km. From these profiles, the fluxes of momentum, heat, and moisture required for each landuse type as input to the dry deposition module must be derived in order to compute deposition velocities using Eqs. (1), (2), and (5). In the current version of the module used in RADM, grid-averaged fluxes are derived from the profiles with semiempirical equations designed to avoid time-consuming iterative calculations that are necessary with the more conventional micrometeorological formulae listed above. This approach is based on the work of Louis (1979) and can in general be used with Eulerian models that provide only grid-averaged profiles to a deposition module that requires estimates of u_* and atmospheric stability. The friction velocity and the Monin-Obukhov length are computed from this information by first computing a bulk Richardson number,

$$R_B = \frac{gz\Delta\theta_v}{\theta_{vg} u^2} , \qquad (16)$$

where $\Delta\theta_v = \theta_{va} - \theta_{vg}$, θ_{va} is potential virtual temperature of the lowest atmospheric layer, θ_{vg} is potential virtual temperature of the ground surface, and u is wind speed.

With the noniterative equations of Louis (1979), the friction velocity is computed for unstable conditions ($R_B < 0$) as

$$u_* = \frac{ku}{\ln \frac{z}{z_o}} \left[1 - \frac{9.4\ R_B}{(1 + 7.4\ B)} \right]^{1/2} , \qquad (17)$$

and for stable conditions ($R_B > 0$) as

$$u_* = \frac{ku}{\ln \frac{z}{z_o}} \left[1 + 4.7\ R_B \right]^{-1} , \qquad (18)$$

where $B = 9.4\ [|R_B| z/z_o]^{1/2}\ [k/\ln(z/z_o)]^2$. The Monin-Obukhov length (L) is computed from

$$L = \frac{\rho c_p \theta_{vg} u_*^3}{kgH} , \qquad (19)$$

where ρ is air density, c_p is the specific heat of air, and H is the heat flux in the lowest atmospheric layer. Heat flux is parameterized by Louis (1979) for unstable conditions ($R_B < 0$) as

$$H = \frac{\rho c_p u \Delta\theta_v}{0.74} \left[\frac{k}{\ln \frac{z}{z_o}} \right]^2 \left[1 - \frac{9.4 R_B}{(1 + 5.3 B)} \right] , \qquad (20)$$

and for stable conditions ($R_B > 0$) as

$$H = \frac{\rho c_p u \Delta\theta_v}{0.74} \left[\frac{k}{\ln \frac{z}{z_o}} \right]^2 [1 + 4.7 R_B]^{-2} . \qquad (21)$$

It is desirable that Eqs. (15) to (19) be compatible with Eqs. (1) to (12) in regard to the values of u_*, H, and L computed with each scheme. This was investigated by calculation of u_* and H with both set of formulae, for typical values of $\Delta\theta_v$, u, z, z_o, etc. It was found that use of k = 0.4 in both schemes produces the same value of u_* within 5%. If k = 0.36 in used in Eqs. (16) to (20), as is most consistent with the other numerical constants in these equations, estimates of u_* are approximately 10% too small. Thus, a value of 0.4 for k should be used in all cases. When comparing estimates of H via Eqs. (19) and (20) with those from Eq. (1) applied to heat [$v_g = H/(\rho c_p \Delta\theta_v)$, $r_g = 0$], however, H via Eqs. (19) and (20) are too large, by as much as 50% in unstable conditions. This is caused partially by the 10% increase in k from 0.36 to 0.4, but is mainly due to the fact that Eqs. (19) and (20) omit a boundary-layer resistance term corresponding to the term $2(D_h/D_g)$ in Eq. (1). This can be rectified by replacing the term $[\ln(z/z_o)]^2$ in the denominator of the second factor on the right-hand sides of Eqs. (19) and (20) with $[\ln(z/z_o)][\ln(z/z_o) + 2]$. This should be done only for rough

surfaces, which in the present module is assumed to be the case when z_o is 0.1 cm or larger. Overall, it is recommended that this conditional replacement be used together with k = 0.4 throughout the calculations. This is all contingent upon the value of θ_{vg} being the temperature on the surface, not a subsurface soil or water temperature.

SECTION 3

SURFACE RESISTANCE

The surface resistance requires special treatment because it is one of the most important, but poorly known, factors in the dry deposition process. It depends not only upon surface characteristics but also upon meteorological conditions and chemical species. Current preliminary acid rain models require estimates of surface deposition rates of SO_2, $SO_4^=$, O_3, NO, NO_2, and HNO_3. These are the species considered included in the present report. For future advanced models, it may be necessary to include H_2O_2, NO_3^- particles, organic peroxides, aldehydes, organic acids, and other organic molecules. Current knowledge is fairly good for SO_2, HNO_3, and O_3, less complete for $SO_4^=$, poor for NO and NO_2, and extremely limited for the others.

On the basis of available information, we attempt to derive a rather comprehensive set of surface resistances for the 11 landuse types, the five seasonal categories, and complete diurnal trends. This approach has several inherent limitations. For example, there is only one landuse type, agricultural lands, to describe a large number of agronomic crops that have different characteristics due to genotype and climatic variations. Clearly, a great deal of generalization is necessary in order to obtain a single value for surface resistance for each landuse type in a certain set of conditions.

Use of surface resistances and Eqs. (1), (2), and (5) assumes that chemical reactions beneath the height at which deposition velocity is computed are very slow compared to the vertical turbulent transfer rates, which might not be valid in all cases. For example, Fitzjarrald and Lenschow (1983) show that the ozone flux can increase dramatically with height above 10 m during the daytime when photochemical reactions involving NO_2 can be important. At night, the reaction of O_3 with NO can cause a decrease of flux with height.

The effects can be considerably more severe for NO and NO_2 considered individually. For this reason, we do not specify deposition velocities for NO and NO_2 separately, but utilize the more self-conserving quantity of the sum of NO plus NO_2, identified as NO_x in this report.

Another difficulty with surface resistance as used here is that it represents a property of the bulk surface, and it is not obvious that certain detailed processes at the surface are, or are not, taken into account. Indeed, some processes such as horizontal advection and the modification of surface uptake by surface nonuniformities are not considered. The step of ignoring the effects of hills, isolated obstacles to flow (e.g., tree windbreaks), and edges between types of surfaces is highly questionable. In all cases, it is assumed that atmospheric stationarity and steady-state exchange processes exist for surfaces in flat terrain that are horizontally homogeneous over distances of at least tens of meters. However, the bulk surface resistances do implicitly take into account a wide range of steady-state processes involving the structure, chemistry, and biological properties of surfaces in flat terrain. For example, the relative amounts of depositon to soil, leaf litter, boles, branches, leaf cuticles, and substomatal leaf surfaces have been considered in adjusting surface resistances to SO_2 deposition to forest canopies as a function of season and solar irradiation.

A large number of studies on the surface uptake rates of various chemical species has been reported, many on the basis of investigations conducted in wind tunnels and exposure chambers of various types. These yield valuable information on the physical, chemical, and biological processes involved in the transfer of pollutants. The evaluations that follow are nevertheless based primarily on field data because these usually provide the ultimate tests. Most of the field information was derived from application of

micrometeorological flux-gradient relationships, eddy correlation, radioactive tracer techniques, and snow sampling.

Table 2 gives samples of the information forming the basis of the tabulations of surface resistances to uptake that are used in the present report. Since the deposition velocities in the Table 2 are not taken at the same height and since they depend on aerodynamic resistances as well as surface resistances, values of the deposition velocity are listed only for rough comparison with predicted results. Table 2 does not list all of the works consulted to derive surface resistances for dry deposition, but only some representative samples. For SO_2 dry deposition there is a very long list of publications available. For sulfate, and submicron particles in general, there are a number of conflicting opinions expressed in the scientific literature; here we rely on the eddy-correlation measurements summarized by Wesely et al. (1985) and omit sulfate as an entry in Table 2. For ozone, only a few of the major references are given and we depend on the summary provided by Wesely (1983). An entirely different situation exists for NO, NO_2, and NO_x. There are very few publications in the refereed scientific literature on the dry deposition velocities of these substances; much of the chamber work in the 1970's (e.g., Judeikis and Wren, 1978)) employed unrealistically high gas concentrations compared to typical outdoor environments.

Values of surface resistance derived here are listed in Table 3 for SO_2 and in Table 4 for O_3. The categories are classified according to solar radiation R in W m^{-2} as follows:

(A & B) $R > 400$,
(C) $400 > R > 200$,
(D) $200 > R > 1$,
(E) $R < 1$ and $u_* > 0.05$ m s^{-1} ,
(F) $R = 0$ and $u_* < 0.05$ m s^{-1} .

TABLE 2. SUMMARY OF RESULTS FROM SELECTED INVESTIGATIONS ON DRY DEPOSITION FOR SO_2, O_3, NO_x, NO_2, AND HNO_3. MEASUREMENT METHODS INCLUDE THOSE INDICATED BY GD FOR GRADIENT AND EC FOR EDDY CORRELATION

Surface	Probable r ($s\ cm^{-1}$)	Deposition velocity ($cm\ s^{-1}$)	Reference/method
SULFUR DIOXIDE			
Pine trees	1.5-5.0	0.1-0.6	Garland and Branson (1977)/ tracer
(dry day)	1-5	0.2-1.0	Fowler & Cape (1983)/GD
(dry night)	5-100	0.01-0.2	
(wet day)	1.5-10	0.1-0.6	
(wet night)	2.5-10	0.1-0.4	
(days mostly sunny)	0.5-2.0	0.72±0.65	Lorenz and Murphy (1985)/GD
Soybeans	0.6	1.3	Dannevik et al. (1976)/GD
Wheat			
(dew cover)	0.0 initially		Fowler & Unsworth (1978)/GD
(winter)	1.6	0.5	Dannevik et al. (1976)/GD
Grass			
(medium height, spring day)	0.6	1.2	Garland (1977)/GD and tracer
(short, spring day)	0.3	0.9	Garland (1977)/GD
(summer days)	0.7	0.7	Owers & Powell (1974)/tracer
(summer day)	0.8	0.8	Shepherd (1974)/tracer
(autumn day)	3.4	0.3	
(summer day)	0.7	0.8	Fowler (1978)/GD
(summer night)	2.0	0.4	
(winter)	1.5	0.5	
(dry surfaces)			
summer day	0.7	0.74	Davies & Mitchell (1983)/GD
night	1.65	0.45	
winter day	1.65	0.54	
night	1.30	0.42	
(wet surfaces)			
summer day	0.08	1.28	
night	0.30	1.00	
winter day	0.55	0.95	
night	1.10	0.41	
Soil	0-0.3	0.5-2.5	Garland (1977)/GD
Water	0.0		Liss (1971)/laboratory studies
Snow	1-2	0.005-0.2	Whelpdale and Shaw (1974)/GD
	~1.0	0.1	Dovland & Eliassen (1976)/ accumulation of S
	~1.0	0.25±0.20	Barrie and Walmsley (1978)/ accumulation of S

TABLE 2 (continued)

OZONE

Deciduous forest			
(winter day)	2.5	0.3	Wesely et al. (1983)/EC
(winter night)	8.0	0.11	
Coniferous (80%) & deciduous (20%) forest, day	0.5	1.0	Lenschow et al. (1982)/EC
Pine forest			
(loblolly, day)	1.4	0.6	Wesely (1983)/EC
(loblolly, night)	12.0	0.8	
(daytime)	0.54	0.45	Lenschow et al. (1982)/EC
Maize			
(daytime trends)	1.0-2.0	0.2-0.5	Wesely (1983)/EC
(senescent, night)	5.7	0.15	Wesely (1983)/EC
(senescent, day)	2.0	0.4	
Soybeans			
(full cover, night)	1.9		Wesely (1983)/EC
(75% cover, night)	1.6	0.3	
Grass			
(short mixed; night & drought)	2.9	0.3	Wesely (1983)/EC
(daytime trend)	0-3.0	0.06-1.0	Delaney and Davies (1983)/GD
Soil	0.2-2		Turner et al. (1973)/EC
(waterlogged)	10.0	0.05	Wesely et al. (1981)/EC
Water			
(fresh)	12-83		Galbally & Roy (1980)/field chamber
	94	0.01	Wesely et al. (1981)/EC
(sea)	12-44		Galbally and Roy (1980)/ field chamber
	18	0.05	Lenschow et al. (1982)/EC
Snow	34.0	0.03	Wesely et al. (1981)/EC
	16.0		Galbally and Roy (1980)/ field chamber

NITROGEN OXIDES

(a) NO_x (assumed to be NO plus NO_2 but might include other N species)

Soybeans			
(daytime)	1.3	0.6	Wesely et al.(1982)/EC
(windy night)	15.0	0.05	Wesely et al.(1982)/EC
Grass			
(daytime)	0.11-2.28	~0.7	Kasting(1980)/GD, cited by Delaney and Davies (1983)
(cut, daytime)	0.8-5.6	0.1-0.6	Delany and Davies (1983)/GD
Snow	>33	<0.03	Granat and Johansson (1983)/ field chamber

(b) HO_2

Scots pine (summer daytime)	1.2-2.5	0.4-0.8	Grennfelt et al. (1983)/GD
Soil & cement	1.3-3.3	0.3-0.8	Judeikis and Wren (1978)/ laboratory chamber

(d) HNO_3

grass, day and night	0.0	1.1-3.6	Huebert (1985)/GD

TABLE 3. SU[illegible]STANCES (S CM^{-1}) FOR SULFUR DIOXIDE FOR VAR[illegible]DUSE TYPES AND INSOLATION CATEGORIES

Land[illegible]	Insolation category				
	A & B	C	D	E	F
			Season 1		
1	5	5	5	5	0.1
2	0.7	1.2	2	4	0.1
3	1	1.4	2	4	0.1
4	0.9	1.5	3	12	0.5
5	1.5	2.4	4	12	0.5
6	0.7	1.4	3	10	0.5
7	0	0	0	0	0
8	10	10	10	10	5
9	0.5	0.6	0.8	1	0.1
10	1	1.4	2	5	0.1
11	1.5	3	4	5	0.2
			Season 2		
1	5	5	5	5	0.5
2	5	5	5	5	1
3	4	4	5	5	1
4	10	10	10	10	1
5	8	8	8	8	1
6	6	6	6	6	1
7	0	0	0	0	0
8	10	10	10	10	5
9	1	1	1	1	0.8
10	4.5	4.5	5	5	1
11	5	5	5	5	1
			Season 3		
1	5	5	5	5	0.5
2	0.5	0.5	0.5	0.5	0.5
3	5	5	5	5	1
4	15	15	15	15	1
5	10	10	10	10	1
6	6	6	6	6	1
7	0	0	0	0	0
8	10	10	10	10	5
9	1	1	1	1	0.8
10	2	2	2	2	1
11	5	5	5	5	1
			Season 4		
1	2	2	2	2	0.5
2	1	1	1	1	1
3	1	1	1	1	1
4	10	10	10	10	10
5	5	5	5	5	5
6	5	5	5	5	5
7	0	0	0	0	0
8	10	10	10	10	5
9	1	1	1	1	1
10	1	1	1	1	1
11	1	1	1	1	1
			Season 5		
1	5	5	5	5	0.1
2	0.5	0.6	0.9	3	0.1
3	1	1.4	2	4	0.1
4	2.5	3.5	5	10	0.5
5	2.5	3.5	5	12	0.5
6	1	2	4	10	0.5
7	0	0	0	0	0
8	10	10	10	10	5
9	0.5	0.6	0.8	1	0.1
10	0.7	1.0	1.5	3.5	0.1
11	3	4	5	5	0.2

TABLE 4. SURFACE RESISTANCES (S CM^{-1}) FOR OZONE FOR VARIOUS LANDUSE TYPES AND INSOLATION CATEGORIES

Landuse	Insolation category				
	A & B	C	D	E	F
			Season 1		
1	3	3	4	4	4
2	0.6	1	1.5	2.5	4
3	0.9	1.2	1.5	3	4
4	0.8	1.3	1.7	12	15
5	1.3	2	3.5	12	15
6	1	2	4	11	15
7	20	20	20	20	20
8	3	3	4	4	4
9	1.5	2	3	10	12
10	0.8	1.1	1.5	3	4
11	1.2	2	3	3	4
			Season 2		
1	3	3	4	4	4
2	2	2	2	2	3
3	1.8	1.8	2	2.5	3
4	2	2	6	10	15
5	3	3	7	12	15
6	3	3	7	10	15
7	20	20	20	20	20
8	3	3	4	4	4
9	2	2	3.5	8	10
10	1.9	1.9	2	2.2	3
11	2	2	3	3	4
			Season 3		
1	3	3	4	4	4
2	1	1	1	1	2
3	2	2	2	2	3
4	3	3	7	20	20
5	3	3	8	20	20
6	3	3	8	20	20
7	20	20	20	20	20
8	3	3	4	4	4
9	8	8	8	8	10
10	1.5	1.5	1.5	1.5	2
11	1.5	1.5	2	3	4
			Season 4		
1	5	5	8	10	10
2	20	20	20	20	20
3	20	20	20	20	20
4	3	4	8	20	20
5	3	4	8	20	20
6	3	4	8	20	20
7	20	20	20	20	20
8	3	3	4	4	4
9	10	10	10	10	10
10	20	20	20	20	20
11	10	10	10	10	10
			Season 5		
1	3	3	4	4	4
2	0.4	0.5	0.8	2	3
3	0.8	1	1.2	3	4
4	2	3	4	10	15
5	2	3	4	12	15
6	1.5	2.0	4	10	15
7	20	20	20	20	20
8	3	3	4	4	4
9	4	4	5	8	10
10	0.6	0.8	1	2.5	3.5
11	1	1.5	2.5	3	3.5

Solar radiation is defined here as the global (direct plus diffuse) irradiation, an energy flux density, received from the sun at a horizontal plane at the surface of the Earth. Dependence upon solar radiation is emphasized because it affects strongly vegetational stomatal openings, which have the major role in controlling surface resistance. At times where R is practically zero, there is one primary category (E) given; the last category (F) is intended only for a surface wetted with dew or frost in very light winds. In some special situations, the categories defined here might be associated with the Pasquill-Gifford categories (e.g., Turner, 1970) used in determining dispersion coefficients for studies of pollutant dispersion, but there is not necessarily a one-to-one correspondence.

Values of surface resistance for NO plus NO_2 are assumed to be 1.75 of ozone values, as reported by Wesely et al. (1982). This is restricted to vegetated surfaces (landuse types 2, 3, 4, 5, 6, 9, and 11) during summer and late spring (seasonal conditions 1 and 5) in the daytime (insolation categories A through D). For all other conditions, the larger of a value of 1.75 multiplied by r_g for ozone, or 10 s cm^{-1}, is assumed. For HNO_3, the surface resistance is assumed to be 0.1 s cm^{-1}. The surface resistances for sulfate particles under various atmospheric conditions are computed from:

$$r_p = \begin{cases} [0.002\ u_*]^{-1}, \text{ for neutural and stable conditions,} \\ \{0.002\ u_*[1 + (-300/L)^{0.667}]\}^{-1}, \text{ unstable,} \\ \{0.0009\ u_*(-z_i/L)^{0.667}\}^{-1}, \text{ if } z_i/L < -30, \end{cases} \quad (22)$$

where z_i is inversion height and L is Monin-Obukhov length (Wesely et al., 1985). These two parameters are assumed to be given by an independent meteorological subroutine. To avoid abnormally large values of deposition velocities for sulfate, their values are not allowed to exceed those listed in Table 5.

TABLE 5. MAXIMUM DEPOSITION VELOCITIES (CM S^{-1}) FOR PARTICULATE SULFATE

landuse	Season				
	1	2	3	4	5
1	0.1	0.1	0.1	0.1	0.1
2	1.0	1.0	1.0	1.0	1.0
3	1.0	1.0	1.0	1.0	1.0
4	1.0	0.1	0.1	0.1	1.0
5	1.0	0.8	0.8	0.8	1.0
6	1.0	0.4	0.4	0.4	1.0
7	0.1	0.1	0.1	0.1	0.1
8	1.0	1.0	1.0	1.0	1.0
9	1.0	1.0	1.0	1.0	1.0
10	1.0	1.0	1.0	1.0	1.0
11	1.0	1.0	1.0	1.0	1.0

Deposition to surfaces wetted by dew or covered by frost is not thoroughly described in the dry deposition module. For SO_2, surface resistances are set to relatively small values in many cases under insolation category F because frost or dew is expected to form under the light-wind nighttime conditions associated with this category. An increase in surface resistance to O_3 removal is expected (Wesely et al., 1978; Wesely, 1983). With this condition, however, aerodynamic resistances are often very large and thus deposition velocites at heights of several meters should be very small for all gases and fine particles. Dew increases the deposition velocity for SO_2 most often when winds are strong after category F has been in effect for a few hours. It is recommended that enhanced deposition of SO_2 because of dew be restricted to such a situation and then for only a period of approximately two hours. After such a suitable time interval, the dew might evaporate or become too acidic to take up more SO_2 (Fowler, 1978; Fowler and Unsworth, 1979). The present module does not make provision for such adjustments.

Wetting of surfaces due to rainfall is not considered in the present module. Depending on the acidity and concentration of SO_2 dissolved in the rainwater, wetting of surfaces by rainfall might increase or decrease the deposition velocity for SO_2, and the length of time over which such changes would take place is unknown. In West Germany, for example, Wesely et al. (unpublished data) found that light rain greatly reduced SO_2 dry deposition velocities during rain and until the surface dried, but had little effect on O_3 uptake. For materials surfaces in urban areas, it might be appropriate to reduce surface resistances to SO_2 uptake to some small value, say 0.1 s cm^{-1}, for as long as 24 hr after rainfall (A. C. Youngdahl and R. A. Livingston, private communication).

SECTION 4

MODULE APPLICATION

LANDUSE DATA

The landuse data used in the present study were prepared for the U. S. EPA by Lockheed Engineering and Management Services, Inc. They were derived from the U.S. Geological Survey Land Use and Land Cover (LULC) map series, Landsat regional mosaic images, and from single-scene Landsat spot coverage. The domain of interest covers an area from 52 to 134 deg west longitude and 24 to 55 deg north latitude. The area is divided into a matrix of 328 x 186 (longitude by latitude) grid cells with increments of 1/4 and 1/6 degree, longitude and latitude, respectively. The landuses are classified into 11 types. Data for each grid cell contain longitude and latitude coordinates of the cell and the percentages of the areas occupied by the 11 landuse types present in the cell. The data for grid cells are stored in a computer file and are arranged by starting at the southeast corner of the domain of interest and proceeding in the order of east to west and south to north. A sample landuse map of the most prevalent landuse type in each one-degree square is shown in Fig. 1. To display in a single alphanumeric character, the landuse types 10 and 11 are represented by A and B, respectively. The landuse type A (mixed agricultural and range land) appears to dominate the landuse of the central United States, and type 5 (coniferous forest) appears to be the most common surface in the parts of Canada shown in Fig. 1.

COMPUTER CODE FOR GENERAL APPLICATIONS

A flow chart for interpolating the computer code developed at Argonne National Laboratory (ANL) is shown in Fig. 2, and the associated computer codes are listed in Appendix 1. The flow chart indicates that there are three

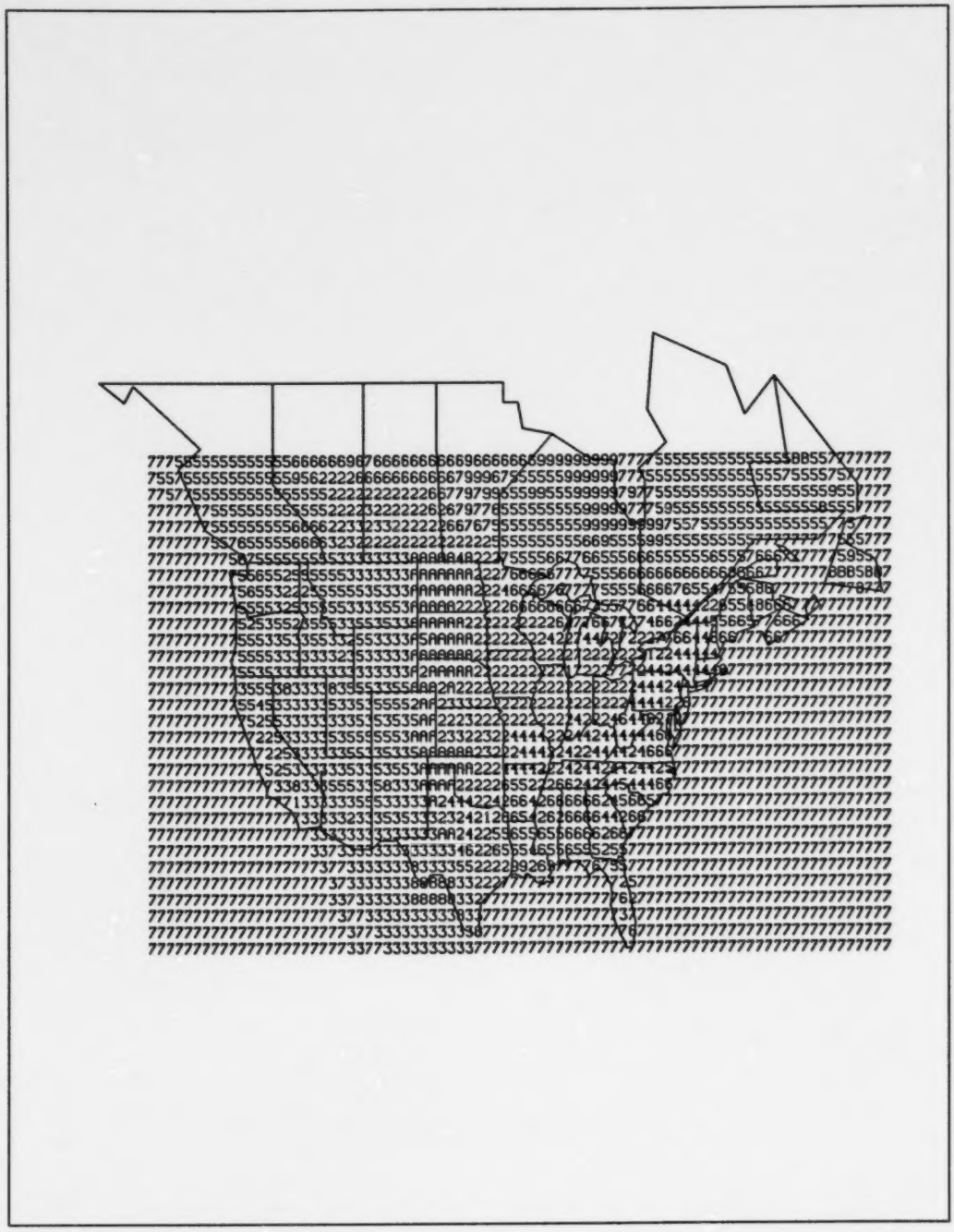

Figure 1. A landuse map of North America with dominant landuse types represented by alphanumeric symbols: 1 (urban land), 2 (agriculture land), 3 (range land), 4 (deciduous forest), 5 (coniferous forest), 6 (mixed forest including wetland), 7 (water), 8 (barren land), 9 (non-forested wetland), A (mixed agricultural and range land), and B (rocky open area occupied by low growing shrubs).

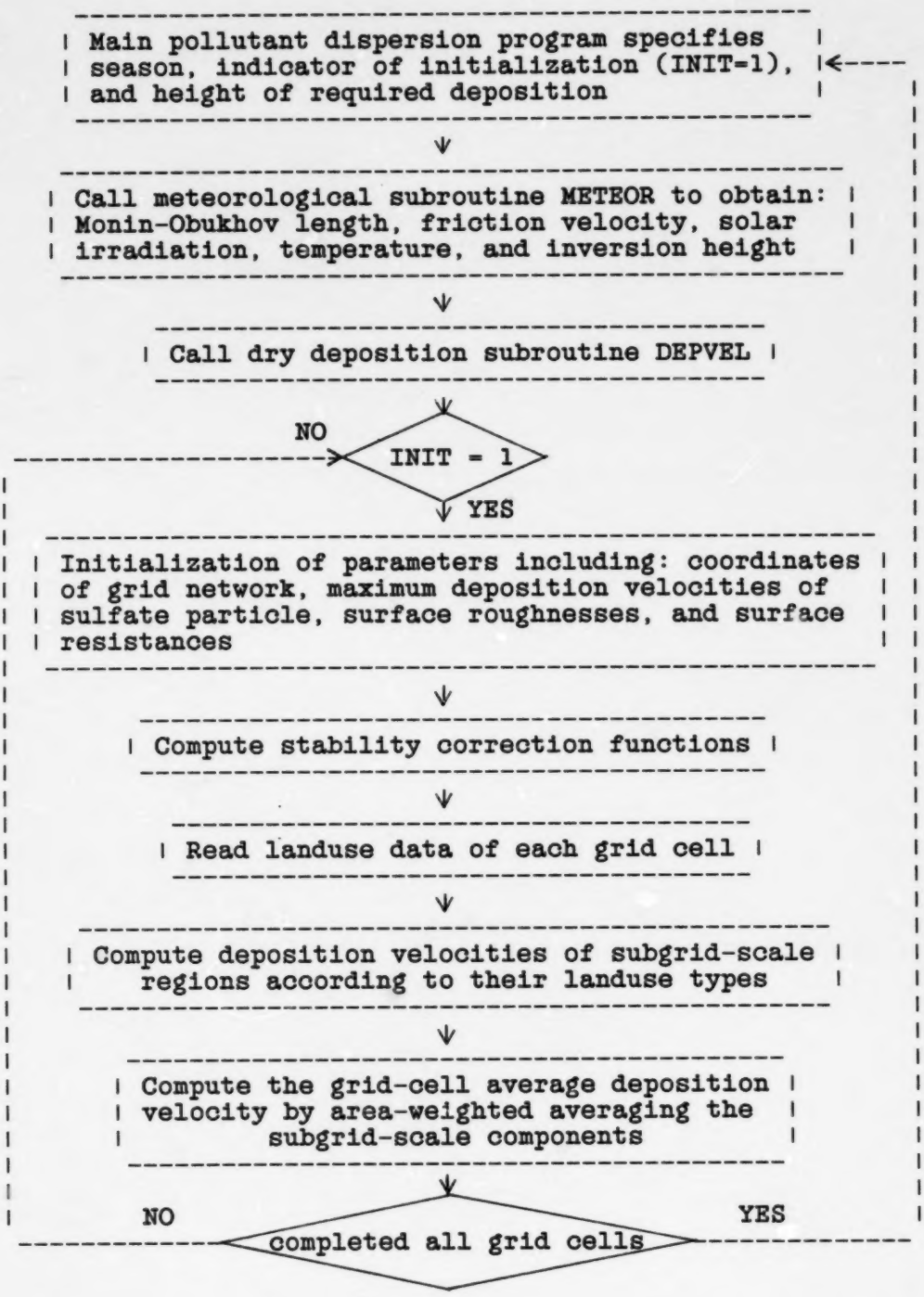
Main pollutant dispersion program specifies season, indicator of initialization (INIT=1), and height of required deposition
Call meteorological subroutine METEOR to obtain: Monin-Obukhov length, friction velocity, solar irradiation, temperature, and inversion height
Call dry deposition subroutine DEPVEL
NO
INIT = 1
YES
Initialization of parameters including: coordinates of grid network, maximum deposition velocities of sulfate particle, surface roughnesses, and surface resistances
Compute stability correction functions
Read landuse data of each grid cell
Compute deposition velocities of subgrid-scale regions according to their landuse types
Compute the grid-cell average deposition velocity by area-weighted averaging the subgrid-scale components
NO
completed all grid cells
YES

Figure 2. Flow chart for ANL dry deposition module.

major components in the program, which are a main program and two subroutines METEOR and DEPVEL. The main program and the meteorological subroutine METEOR are hypothetical, and used here only as examples to demonstrate the peripheral conditions most likely to be encountered in an application of the dry deposition subroutine DEPVEL. The main program would normally simulate pollutant transport and diffusion and METEOR would provide the specific variables needed to compute dry deposition velocities near the surface boundary.

The flow chart shows that values of the parameters INIT (an indicator of initialization), ISESN (season number), and the height of interest have to be specified in the main program before the subroutine DEPVEL is called for the first time. Before the DEPVEL is called each time, the subroutine METEOR has to be called to produce new values of meteorological variables to be used in DEPVEL. These variables are RADIAT (solar radiation), TCZ (temperature at the height of interest), and ZINV (inversion height). Values of meteorological parameters are assigned in the subroutine METEOR. To obtain more realistic estimates of subgrid-scale friction velocity, the product of friction velocity and mean wind speed is assumed to be constant for a horizontal grid area. The product is expected to be given by the subroutine METEOR, and is used in conjunction with local surface roughnesses to compute local friction velocities. With these parameters as input, the subroutine DEPVEL is called and the deposition velocities are produced. After the DEPVEL is called, the indicator INIT is set to zero so that calculations of some of the parameters will not be unnecessarily repeated. However, if the season is changed during a simulation, INIT has to be set to 1 to permit reinitialization of parameters dependent upon seaonal variations.

The results of calling DEPVEL will be the deposition velocities storing in the matrices VDS2(I,J), VDS04(I,J), VD03(I,J), VDNOX(I,J), and VDHN03(I,J) for sulfur dioxide, sulfate, ozone, NO plus NO_2, and HNO_3, respectively, where values of the indices are arranged in an ascending order from east to west for I and from south to north for J. The results can be directed to a printer or a computer file by calling the subroutine OUTPUT.

Sample maps of dry deposition velocities for SO_2, $SO_4^=$, O_3, NO_x, and HNO_3 at a height of 10 m for summer daytime conditions are shown in Figs. 3 to 7. In all cases, solar irradiation levels greater than 400 W m^{-2} and moderate wind speeds that would correspond to approximately 3.8 m s^{-1} at a height of 10 m above a surface with z_o equal to 3 cm, were assumed. A sensible heat flux of 150 W m^{-2} is assumed over all land surfaces and 20 W m^{-2} is assumed for water surfaces.

NCAR DRY DEPOSITION MODULE

As an example for a special application of the dry deposition model, the flow chart and the computer code of the dry deposition subroutine used by the NCAR Regional Acid Deposition Model (RADM) are shown in Fig. 8 and Appendix 2, respectively. Some of the numerical values for resistances and z_o in Appendix 2 are different from those in Appendix 1 because of the last minute improvements not yet utilized by the RADM version. Also, the geographical area utilized is restricted to a smaller area, and landuse types 8 (barren land) and B (rocky open areas occupied by low growing shrubs) are not used. The RADM version chooses insolation category F when the surface dewpoint temperature is less than the surface air temperature and thus is more realistic than the ANL general version which chooses F when u_* very small at night.

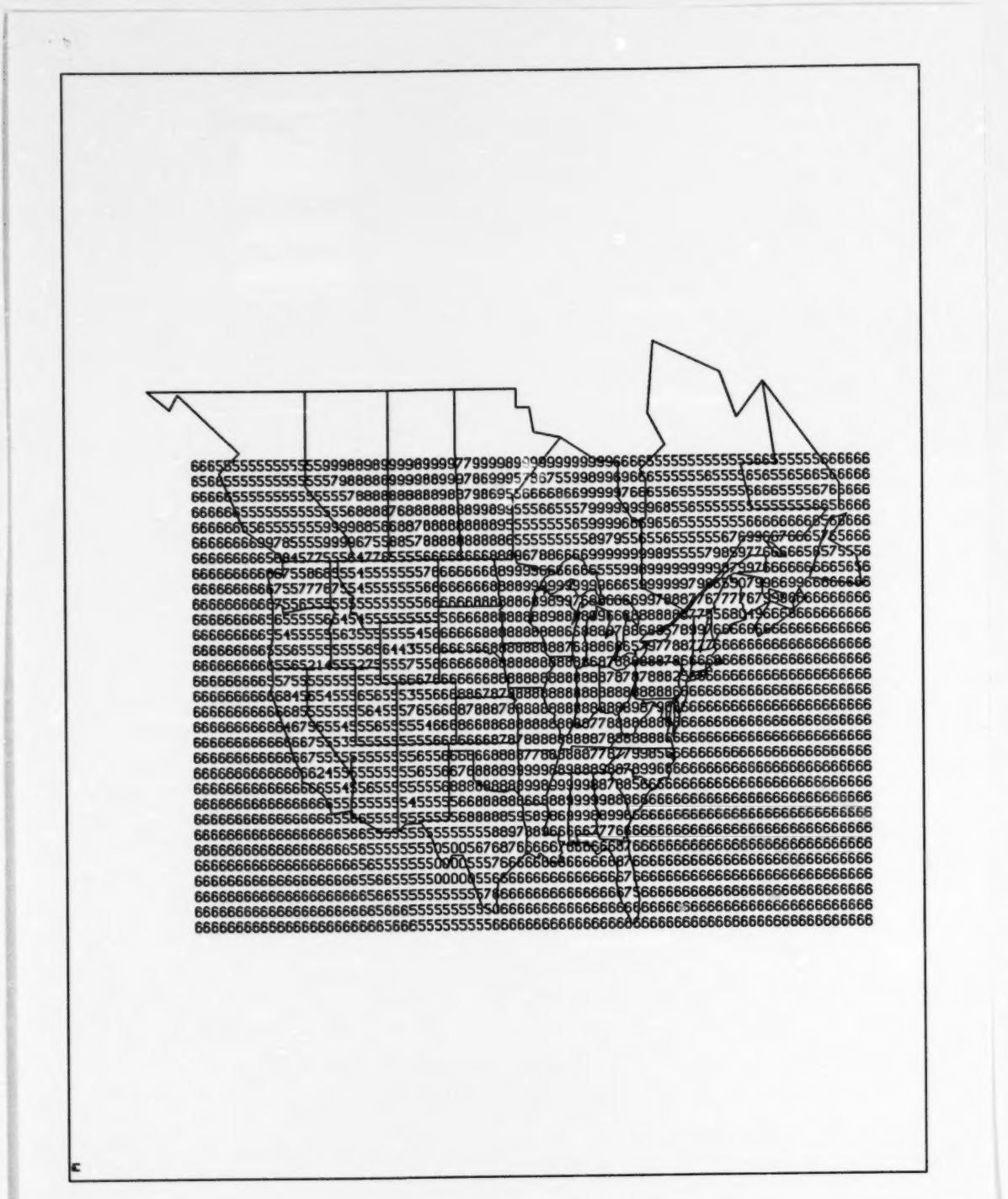

Figure 3. A dry deposition velocity map for SO_2 for summer daytime conditions. The integers (0,1,---, and 9) in the map represent deposition velocities with intervals of 0.117 cm s^{-1}; e.g., 0 and 1 represent the ranges of deposition velocities 0 to 0.117 and 0.117 to 0.234 cm s^{-1}, respectively.

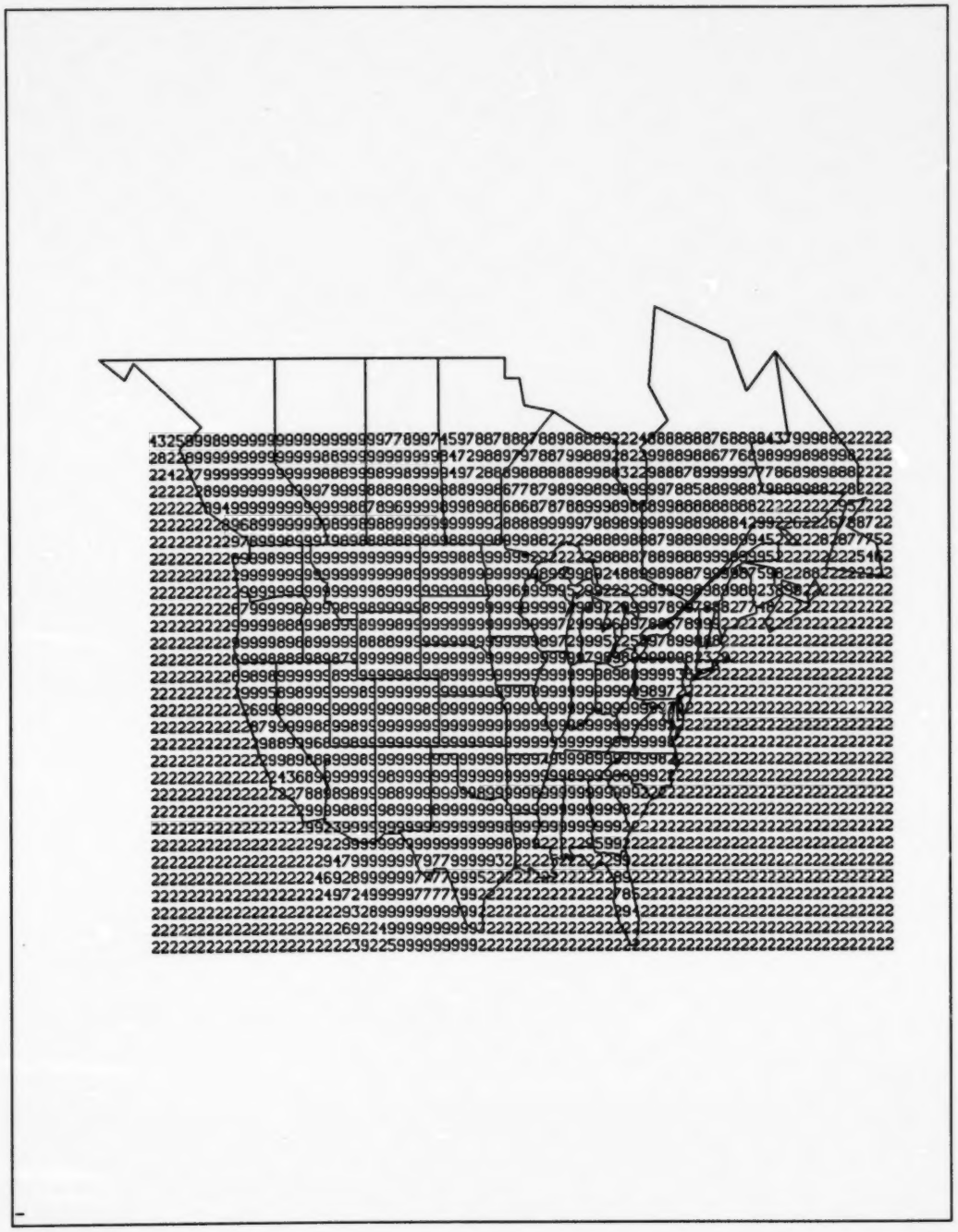

Figure 4. A deposition velocity map for $SO_4^=$, as in Figure 3 except with deposition velocity intervals of 0.0412 cm s^{-1}.

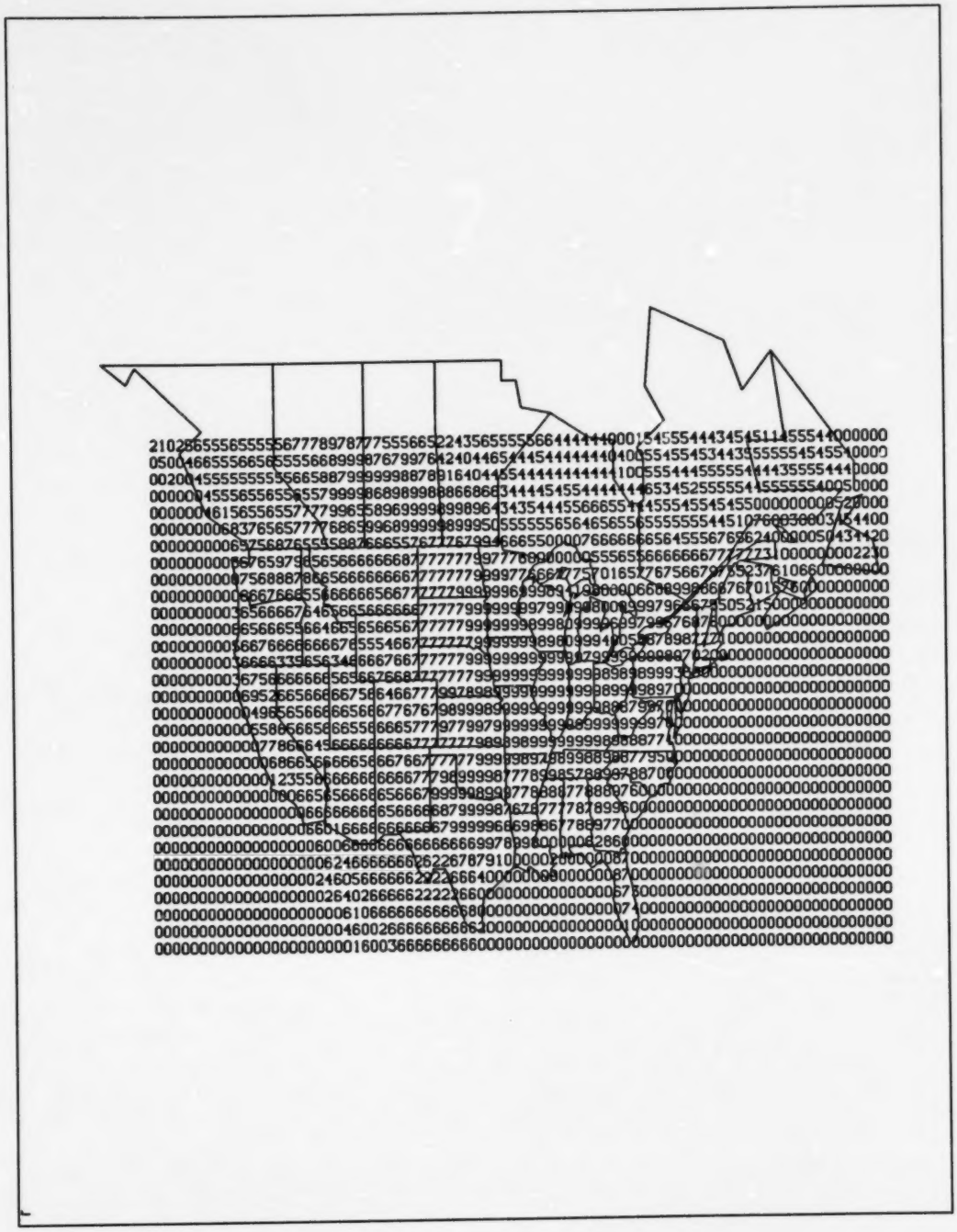

Figure 5. A deposition velocity map for O_3, as in Figure 3 except with deposition velocity intervals of 0.113 cm s^{-1}.

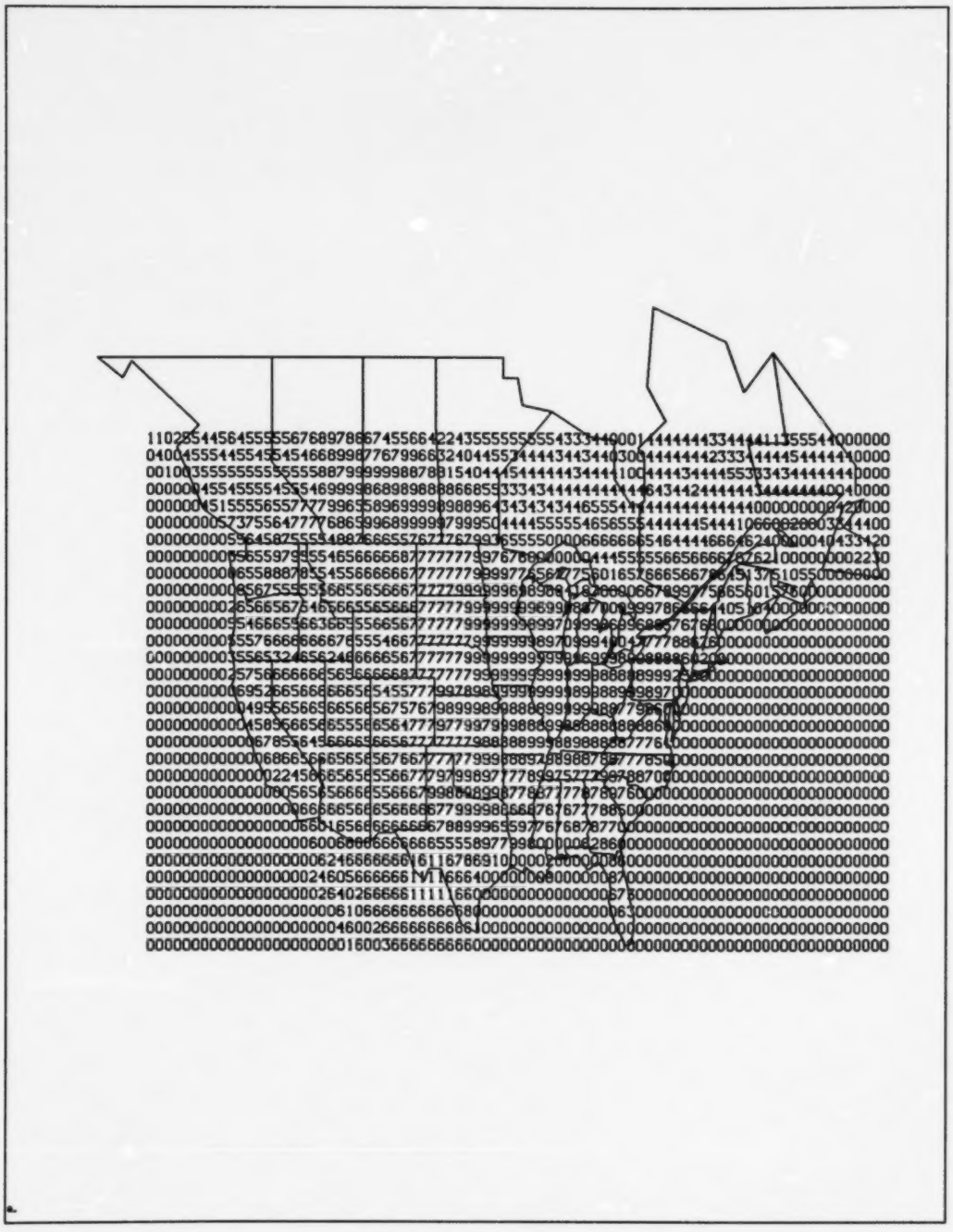

Figure 6. A deposition velocity map for NO_x, as in Figure 3 except with deposition velocity intervals of 0.0751 cm s^{-1}.

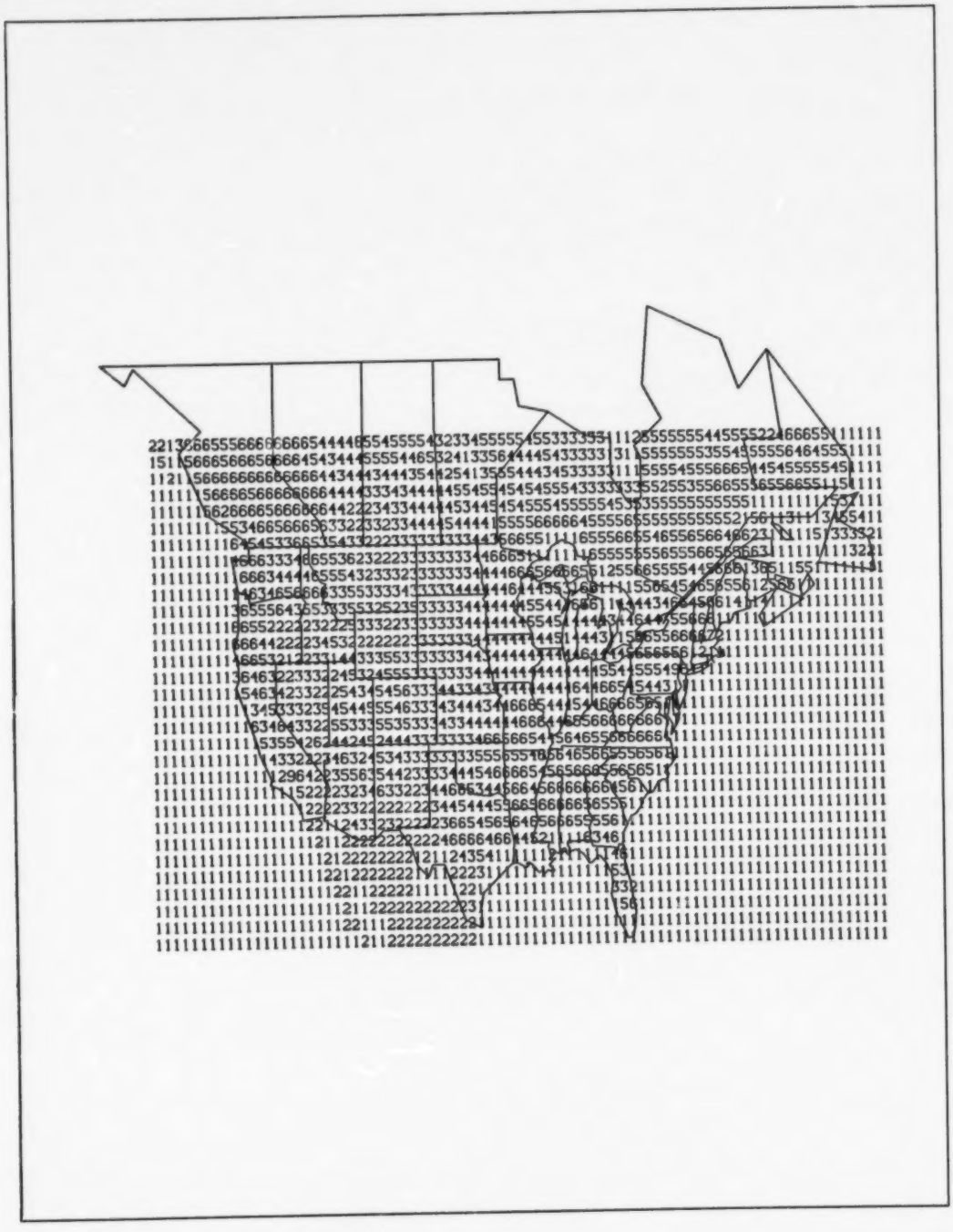

Figure 7. A deposition velocity map for HNO_3, as in Figure 3 except with deposition velocity intervals of 0.596 cm s^{-1}.

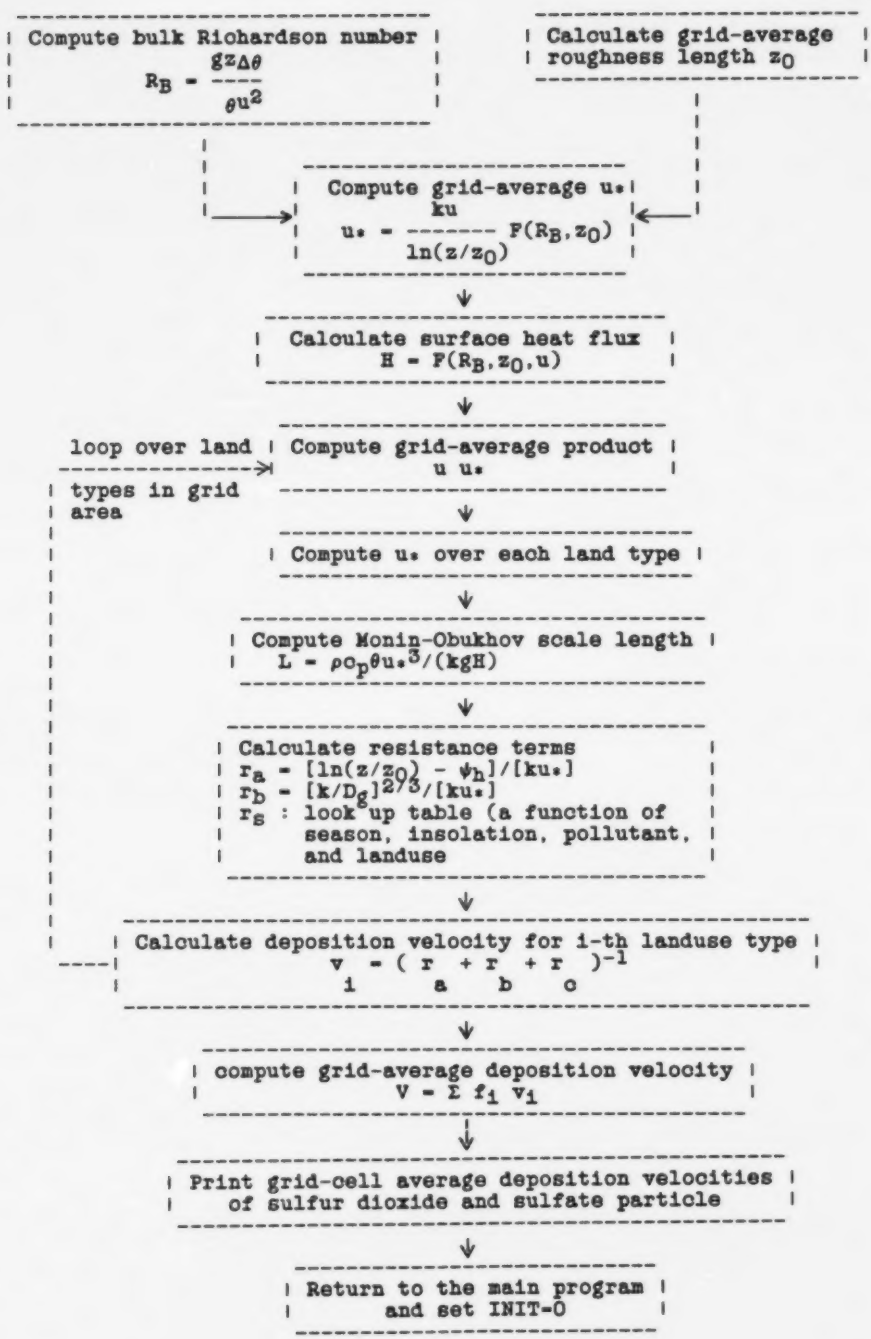
Compute bulk Richardson number
$R_B = \frac{gz\Delta\theta}{\theta u^2}$
Calculate grid-average roughness length z_0
Compute grid-average u_*
$u_* = \frac{ku}{\ln(z/z_0)} F(R_B, z_0)$
Calculate surface heat flux
$H = F(R_B, z_0, u)$
loop over land types in grid area
Compute grid-average product
$u\ u_*$
Compute u_* over each land type
Compute Monin-Obukhov scale length
$L = \rho c_p \theta u_*^3/(kgH)$
Calculate resistance terms
$r_a = [\ln(z/z_0) - \psi_h]/[ku_*]$
$r_b = [k/D_g]^{2/3}/[ku_*]$
r_s : look up table (a function of season, insolation, pollutant, and landuse
Calculate deposition velocity for i-th landuse type
$v_i = (r_a + r_b + r_c)^{-1}$
compute grid-average deposition velocity
$V = \Sigma f_i v_i$
Print grid-cell average deposition velocities of sulfur dioxide and sulfate particle
Return to the main program and set INIT-0

Figure 8. Flow chart for NCAR deposition module.

The computer codes consist of a main program and a subroutine. The main program is to specify input information before the dry deposition subroutine is called. Due to the size and computational cost associated with the NCAR model, the program is written to take advantage of certain computational efficiency features of the CRAY computer on which it is run. The program is a general FORTRAN program which can be run on any machine. One of the efficiency features of the CRAY is its ability to perform vector processing over certain loops within the computational code. For the code shown here, deposition velocities are computed within a vector loop along a north-south direction indicated by J. In this fashion, a one dimensional north-south array of deposition velocities are computed during each call to the subroutine DRYDEP. As a result, north-south arrays of each input parameter are needed before the subroutine can be called. These inputs can be broadly divided into geographical and temporal information, and meteorological information, as listed below:

(A) Geographical and temporal information for N-S array of grid cells,

latitude (deg)
longitude (deg)
height above surface (m)
Julian date
season
landuse distribution

(B) Meteorological information,

temperature of air at observation height (K)
ground temperature (K)
N-S component of wind speed (m/s)
E-W component of wind speed (m/s)
surface pressure (centibars)
planetary boundary height (m)
water vapor mixing ratio (g/g) at observation height
hourly precipitation amount (cm)

Once matrices of these parameters are specified along a given north-south line in the modeling domain, the subroutine DRYDEP is called to compute a matrix of deposition velocities along the N-S line.

The computational flow chart in Fig. 8 shows that an average friction velocity for each grid cell is estimated on the basis of the grid-average wind speed and a surface roughness computed as the logarithmic average via Eq. (14) of those obtained from the landuse map. To calculate friction velocities over each landuse type, the products of wind speed and friction velocity are assumed constant at a specified height near 40 m, as in Eq. (15). Once the friction velocity and the stability correction function are calculated for all landuse types within a grid cell, the subroutine computes the corresponding aerodynamic and sublayer resistances and chooses the appropriate surface resistances to calculate deposition velocities. A grid average deposition velocity is then computed as the area-weighted average of the deposition velocity for each landuse type, as in Eq. (13).

A more thorough account of the dry deposition module as used in RADM is given by Walcek et al. (1986), who successfully utilize the dry deposition module to compute deposition of SO_2, $SO_4^=$, and HNO_3 over eastern United States for three days in the spring. Domain-averaged midday deposition velocities are computed to be 0.8 cm s^{-1} for SO_2, 0.2 cm s^{-1} for sulfate, and 2.5 cm s^{-1} for HNO_3. At night, the deposition velocities likewise computed are approximately 50%, 45%, and 70% of the daytime values, respectively. Sensitivity tests described by Walcek et al. show that the assumption of a constant value for the product of friction velocity and wind speed over a given grid cell is superior to assuming that either one is constant. Also, calculations indicate that the domain-averaged SO_2 deposition velocity increases by a factor of two when the surface is wetted by water low in acidity and SO_2 content, but this is unlikely for rainwater in all cases.

SECTION 5

CONCLUSION

The present report provides a description of a computer subroutine for computing surface dry deposition velocities of major chemical compounds for numerical modeling of acid deposition. Although the subroutine was designed originally for an Eulerian numerical grid model, it is quite general. It can be used to produce dry deposition velocities for other types of numerical models. To run the module, landuse data stored in a file defined as Unit 10 in the computer program has to be provided. Input parameters to be specified before using the module are height, Monin-Obukhov length, friction velocity, solar radiation, atmospheric temperature, and inversion height. The subroutine will produce deposition velocities for SO_2, $SO_4^=$, O_3, NO plus NO_x, and HNO_3 at each grid cell with a dimension of 1/4 and 1/6 deg longitude and latitude, respectively, for the continental United States and surrounding regions. Insufficient information on surface resistances is one of the main limitations to constructing an accurate dry deposition module. Current knowledge of the resistances is fairly good for SO_2, HNO_3 and O_3, fair for $SO_4^=$, and poor in NO and NO_2. The effects of surface wetness are poorly understood, and are not handled explicitly in the dry deposition module, although values of surface resistances for SO_2 and O_3 when the surface is wetted by dew or covered by frost are suggested. The subroutine can be used for other gaseous species if their surface resistances are available. To improve the calculations, more research is needed to acquire the information on the surface resistances of these and other chemical species that are important in studies of acid rain.

The approach of relying on bulk surface resistances provides for an efficient dry deposition module but does not facilitate consideration of

additional chemical species. That is, the factors that control surface resistances are not explicit and thus unavailable for manipulation by the user. Other deficiencies include ignoring such factors as rapid in-air chemical reactions, and the effects of noniform and hilly terrain.

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APPENDICES

LIST OF APPENDICES

1. The computer codes of an ANL Dry Deposition Module..... 43

2. The computer codes of a NCAR Dry Deposition Module..... 52

APPENDIX 1 THE COMPUTER CODES OF AN ANL DRY DEPOSITION MODULE

```
//ANLDEP   JOB USER=B22882,PASSWORD=JCS,CLASS=W,
//         REGION=3300K,TIME=5
//*MAIN ORG=RM080,LINES=5
// EXEC FLICLG
//SYSIN DD *
C
C*** A DRY DEPOSITION MODULE PREPARED BY C. M. SHEIH AND
C    M. L. WESELY FOR A NCAR ACID-RAIN MODEL.
C    THE MAIN PROGRAM AND THE SUBROUTINE METERO SHOWN BELOW
C    ARE USE ONLY AS AN EXAMPLE FOR THE USE OF THE DEPOSITION
C    VELOCITY SUBROUTINE DEPVEL.
C    THE FIRST VERSION WAS COMPLETED ON 2/21/84
C    THE LATEST MODIFICATION COMPLETED ON 6/11/86
C
C*** MAIN PROGRAM OF TRANSPORT MODEL(TO BE CONSTRUCTED BY NCAR)
C
      LOGICAL*1 COM(70),DUMMY(70)
      DIMENSION VDS2(328,186),VDS4(328,186),VDO3(328,186),
     1  VDNOX(328,186),VDHNO3(328,186),HV(328,186),
     2  USTAR(328,186),UUSTAR(328,186),RADIAT(328,186),TCZ(328,186),
     3  ZINV(328,186)
      COMMON/DRYVEL/ IZO(11),ZO(11),RS2(11,6),RO3(11,6),
     1  CXO(328),CYO(186),VDSMAX(11)
C
C*** DEFINE SEASON AND HEIGHT OF REQUIRED DEPOSITION VELOCITY
      INIT=1
      CZ=10.
      ISESN=1
      ITIME=0
   10 ITIME=ITIME+1
C*** CALL METERO TO OBTAIN METEROOLOGICAL PARAMETERS FOR
C    COMPUTATION OF DEPOSITION VELOCITY
      CALL METERO(HV,USTAR,UUSTAR,RADIAT,TCZ,ZINV)
      CALL DEPVEL(VDS2,VDS4,VDO3,VDNOX,VDHNO3,INIT,CZ,ISESN,
     1  HV,USTAR,UUSTAR,RADIAT,TCZ,ZINV)
C
C*** INIT=1 DEFINED INITIALLY IN DATA ASSIGNMENT TO PERMIT
C    INITIALIZATION OF PARAMETERS ONLY ONCE AND THEN SET INIT=0
C    TO BYPASS INITIALIZATION IN SUBROUTINE DEPVEL
C
      INIT=0
      IF(ITIME.LT.1) GOTO 10
      STOP
      END
      SUBROUTINE METERO(HV,USTAR,UUSTAR,RADIAT,TCZ,ZINV)
C*********************************************************
C*** METEROOLOGICAL MODULE
      DIMENSION HV(328,186),USTAR(328,186),UUSTAR(328,186),
     1  RADIAT(328,186),TCZ(328,186),ZINV(328,186)
      LONOB=328
      LATOB=186
      CU=3.9
```

```
      DO 10 I=1,LONOB
      DO 10 J=1,LATOB
C*** THESE DUMMY VALUES ARE ONLY TO PROVIDE A TEST CASE
      HV(I,J)=150.
      USTAR(I,J)=0.30
      UUSTAR(I,J)=CU*USTAR(I,J)
      RADIAT(I,J)=500.
      TCZ(I,J)=25.
      ZINV(I,J)=1000.
   10 CONTINUE
      RETURN
      END
      SUBROUTINE DEPVEL(VDS2,VDS4,VDO3,VDNOX,VDHNO3,INIT,CZ,ISESN,
     1  HV,USTAR,UUSTAR,RADIAT,TCZ,ZINV)
C*******************************************************************************
C
C*** THIS SUBROUTINE IS CONSTRUCTED BY C. M. SHEIH AND
C    M. L. WESELY OF ARGONNE NATIONAL LABORATORY FOR
C    COMPUTING DRY DEPOSITION VELOCITIES FOR SO2, SO4,
C    OZONE, NOX, AND HNO3.
C    INPUT PARAMETERS ISESN, ---, AND ZINV AND OTHER CODE
C    NAMES ARE DEFINED BELOW:
C    INIT-1(YES) OR 0(NO) FOR INITIALIZATION OF PARAMETERS.
C    ISESN-1(MIDSUMMER), 2(AUTUMN WITH UNHARVESTED CROPLAND),
C          3(LATE AUTUMN AFTER FROST), 4(WINTER-SNOW ON GROUND),
C          AND 5(TRANSITIONAL, SPRING & PARTIALLY GREEN SHORT
C          ANNUALS)
C    HV=VIRTUAL HEAR FLUX (W/M**2)
C    USTAR-FRICTION VELOCITY (M/S)
C    RADIAT-SOLAR RADIATION (W/M**2)
C    CZ-HEIGHT(M) WHERE DEP VELOCITIES ARE NEEDED
C    TCZ-TEMPERATURE AT CZ
C    ZINV=INVERSION HEIGHT (M)
C    VDS2-SO2 DEPOSITION VELOCITY (M/S)
C    VDS4-SO4 DEPOSITION VELOCITY (M/S)
C    VDO3, VDNOX & VDNHO3 = DEP VEL OF O3, NOX & O3
C    VDSMAX-MAX PERMISSIBLE SURF SO4 DEP VEL FOR VARIOUS LANDTYPES
C           AND SEASONS
C
C*** COMPUTE DEPOSITION VELOCITIES BY USE OF SURFACE
C    LANDUSE AND LAND COVER INVENTORY PREPARED BY
C    S. H. PAGE OF LOCKHEED ENGINEERING AND MANAGEMENT SERVICES
C    INC., REMOTE SENSING LABORATORY LAS VEGAS, NEVADA 89114
C    RESULTED FROM THE CONTACT OF MARV WESELY WITH FRANK BINKOWSKI
C    FTS 629-2460
C*** 5/24/85 THE COMPUTER CODES ARE MODIFIED TO INCORPORATE
C    LANDUSE TYPES 8 AND 11 ACCORDING TO THE DATA COMPILED BY
C    BINKOWSKI. THE NEW DATA SET IS ARRANGED IN LATITUDE DEGREE,
C    # OF 1/12 LAT DEG (WHICH IS AT THE GRID CENTER AND THE GRID
C    INCREMENTS ARE 1/6 DEG), LON DEG, # OF 1/8 LON DEG (WITH
C    INCREMENTS OF 1/4 DEG), AND 11 VALUES OF % LANDUSES.  THE
C    GRID DOMAIN IS LONGITUDE 52 1/8-133 7/8 DEG BY LATITUDE 24 1/12
C    -54 11/12 OR COVERING LON 52-134 BY LAT 24-55 DEG, OR NX-328 AND
C    NY-186. GRID POINTS START FROM THE S.E. CORNER AND RUNS
```

```
C     FROM E. TO W AND FROM S. TO N.
C
C        LAND-USE TYPES
C
C      1 URBAN LAND
C      2 AGRICULTURAL LAND
C      3 RANGE LAND
C      4 DECIDUOUS FOREST
C      5 CONIFEROUS FOREST
C      6 MIXED FOREST INCLUDED WETLAND
C      7 WATER(SEAWATER ASSUMED)
C      8 BARREN LAND
C      9 NON-FORESTED WETLAND
C     10 MIXED AGRICULTURAL AND RANGE
C        LAND
C     11 ROCKY OPEN AREAS OCCUPIED BY LOW GROWING SHRUBS
C
       LOGICAL*1 COM(70),DUMMY(70)
       DIMENSION VDS2(328,186),VDS4(328,186),VDO3(328,186),
      1  VDNOX(328,186),VDHNO3(328,186),HV(328,186),
      2  USTAR(328,186),UUSTAR(328,186),RADIAT(328,186),TCZ(328,186),
      3  ZINV(328,186),LATLON(4),IUSE(11)
       COMMON/DRYVEL/ IZO(11),ZO(11),RS2(11,6),RO3(11,6),
      1  CXO(328),CYO(186),VDSMAX(11)
C
       IF(INIT.NE.1) GOTO 41
C*** SETUP COORDINATES FOR THE GRID NETWORK
       LONOB=328
       LATOB=186
       C1=52.-1./8.
       DO 10 I=1,LONOB
    10 CXO(I)=C1+I/4.
       C1=24.-1./12.
       DO 12 J=1,LATOB
    12 CYO(J)=C1+J/6.
C*** MAXIMUM PERMISSIBLE SO4 DEP VEL FOR LANDTYPES 1-11
       DO 16 L=1,5
       IF(L.NE.ISESN) GOTO 14
       READ(5,1111) COM,(VDSMAX(I),I=1,11)
 1111 FORMAT(70A1/(11F6.3))
       PRINT 1112, COM,(VDSMAX(I),I=1,11)
 1112 FORMAT('0',70A1/(' ',11F6.3))
       GOTO 16
    14 READ(5,1111) COM,(C1,I=1,11)
    16 CONTINUE
C*** READ A DUMMY LINE
       READ(5,1100) DUMMY
C*** READ IZO OF PROPER SEASONS (ISESN=1 IS SUMMER)
       DO 22 L=1,5
       IF(L.NE.ISESN) GOTO 20
       READ(5,1211) COM,(IZO(I),I=1,11)
 1211 FORMAT(70A1/11I6)
       PRINT 1212, COM,(IZO(I),I=1,11)
 1212 FORMAT('0',70A1/(' ',11I6))
```

```
      GOTO 22
   20 READ(5,1211) COM,(IC1,I=1,11)
   22 CONTINUE
C*** READ SURFACE RESISTANCES OF SO2; L IS SEASON; LL IS STAB.
      READ(5,1100) COM
      PRINT 2224, COM
      DO 28 L=1,5
      IF(L.NE.ISESN) GOTO 25
      DO 24 LL=1,6
      IF(LL.NE.1) GOTO 23
      READ(5,1100) COM
      PRINT 2224, COM
   23 READ(5,1311) CAT,(RS2(I,LL),I=1,11)
 1311 FORMAT(A1,2X,11F6.0)
   24 PRINT 1314, CAT,(RS2(I,LL),I=1,11)
 1314 FORMAT('0',A1,2X,11F6.0)
      GOTO 28
   25 DO 27 LL=1,6
      IF(LL.NE.1) GOTO 26
      READ(5,1100) COM
   26 READ(5,1311) CAT,(C1,I=1,11)
   27 CONTINUE
   28 CONTINUE
C*** READ SURFACE RESISTANCES OF OZONE
      READ(5,1100) COM
      PRINT 2224, COM
      DO 38 L=1,5
      IF(L.NE.ISESN) GOTO 35
      DO 34 LL=1,6
      IF(LL.NE.1) GOTO 33
      READ(5,1100) COM
      PRINT 2224, COM
   33 READ(5,1311) CAT,(RO3(I,LL),I=1,11)
   34 PRINT 1314, CAT,(RO3(I,LL),I=1,11)
      GOTO 38
   35 DO 37 LL=1,6
      IF(LL.NE.1) GOTO 36
      READ(5,1100) COM
   36 READ(5,1311) CAT,(C1,I=1,11)
   37 CONTINUE
   38 CONTINUE
CC    REWIND 5
C*** CONVERT TO APPROPRIATE UNITS
      DO 40 I=1,11
      ZO(I)=IZO(I)*1.E-4
   40 CONTINUE
   41 CONTINUE
C
C*** ENDING OF PARAMETER INITIALIZATION AND BEGINNING
C    OF COMPUTING DEP VELOCITIES
C
C*** READ LANUSE DATA
      READ(10,2222) N
 2222 FORMAT(I5)
```

```
      PRINT 2223, N
 2223 FORMAT('0','TOTAL LINES OF COMMENTS =',I5)
      DO 42 I=1,N
      READ(10,1100) COM
 1100 FORMAT(70A1)
   42 PRINT 2224, COM
 2224 FORMAT(' ',70A1)
      DO 68 J=1,LATOB
      DO 68 I=1,LONOB
      VDS2(I,J)=0.
      VDS4(I,J)=0.
      VDO3(I,J)=0.
      VDNOX(I,J)=0.
      VDHNO3(I,J)=0.
      C1=(273.+TCZ(I,J))/273.
      C2=C1**1.75*1.0E-04
      DCS2=0.116*C2
      DCO3=0.134*C2
      DCNOX=0.140*C2
      DCHNO3=0.118*C2
      XNU=0.151*C1**1.77*1.0E-04
C*** CLASSIFICATION OF SURFACE RESISTANCES ACCORDING TO
C    SOLAR RADIATION R (W/M**2) FOR CATEGORIES (A & B)
C    R>400, (C) 400>R>200, (D) 200>R>1, (E) R=0 AND
C    USTAR>0.05 M/S, AND (F) R=0 AND USTAR<0.05 M/S.
      ICAT=1
      IF(RADIAT(I,J).GT.1.) GOTO 43
      ICAT=6
      IF(USTAR(I,J).GT.0.05) ICAT=5
      GOTO 44
   43 IF(RADIAT(I,J).LT.400.) ICAT=3
      IF(RADIAT(I,J).LT.200.) ICAT=4
   44 CONTINUE
C*** READ LANDUSE DATA
      READ(10,2400,END=99) LATLON,IUSE
 2400 FORMAT(4I4,11I5)
      DO 68 LL=1,11
      IF(IUSE(LL).EQ.0) GOTO 68
C*** TRANSFER HEAT FLUX TO CHV TO AVOID BEING ERASED
      CHV=HV(I,J)
      IF(LL.NE.7) GOTO 45
C*** SET FOR WATER THE ROUGHNESS AND HEAT FLUX
      ZO(7)=1.4E-02*USTAR(I,J)*USTAR(I,J)/9.8
     1  +1.1E-01*XNU/USTAR(I,J)
      CHV=20.
   45 CONTINUE
C*** COMPUTE LOCAL USTAR BY ASSUMING U*USTAR OR UUSTAR=CONST
C    FIRST CHOICE ASSUMES NEUTRAL CONDITIONS
      CUSTA=SQRT(0.4*UUSTAR(I,J)/(ALOG(CZ/ZO(LL))))
      ICNT=0
C*** START ITERATION
   46 XX=CUSTA
      C1=-0.00327*CZ*CHV/((273.+TCZ(I,J))*USTAR(I,J)**3.)
      IF(C1.LT.0.) GOTO 47
```

```
      IF(C1.GE.1.) C1=0.99
      SIM=-5.*C1
      GOTO 48
   47 IF(C1.LE.-1.) C1=-0.99
      C2=ALOG(-C1)
      SIM=EXP(0.032+0.448*C2-0.132*C2*C2)
   48 CONTINUE
      IF(LL.EQ.7) ZO(7)=1.4E-02*USTAR(I,J)*USTAR(I,J)/
     1  9.8+1.1E-01*XNU/USTAR(I,J)
      CUSTA=SQRT(0.4*UUSTAR(I,J)/(ALOG(CZ/ZO(LL))-SIM))
      ERR=ABS((CUSTA-XX)/XX)
      ICNT=ICNT+1
      IF(ICNT.GT.5) GOTO 49
      IF(ERR.GT.0.01) GOTO 46
   49 SIC=SIM
C*** PRINT SAMPLE USTAR
      IF(MOD(I,100).NE.0) GOTO 50
      IF(J.NE.150) GOTO 50
      PRINT 2800, CUSTA,LL
 2800 FORMAT(' ','CUSTA =',E12.3,4X,'FOR LANDUSE =',I2)
   50 CONTINUE
      IF(C1.LT.0.) SIC=EXP(0.598+0.39*C2-0.09*C2*C2)
      CKUSTA=0.4*CUSTA
      OBKHOV=CZ/C1
C*** SO4 SURFACE DEP VEL PARAMETERS
      VDS=0.002*USTAR(I,J)
      IF(OBKHOV.LT.0.) VDS=VDS*(1.+(-300./OBKHOV)**0.6667)
      C1=ZINV(I,J)/OBKHOV
      IF(C1.LT.-30.) VDS=0.0009*USTAR(I,J)*(-C1)**0.6667
C*** SET VDS TO BE LESS THAN VDSMAX
      CVDS=VDS
      IF(CVDS.GT.VDSMAX(LL)) CVDS=VDSMAX(LL)
C*** RNOX SET TO 1.75(RO3) FOR LANDUSE TYPES 2,3,4,5,6,9,10
C    AND 11 AND FOR SUMMER AND LATE SPRING (SEASONAL CONDITIONS
C    1 AND 5) IN THE DAYTIME (INSOLATION CATEGORIES A THROUGH D.
C    FOR OTHER CONDITIONS, THE LARGER OF A VALUE OF 1.75*RO3 OR
C    10 S/CM OR 1000 S/M.
      RNOX=1.75*RO3(LL,ICAT)
      IF(ISESN.NE.1.AND.ISESN.NE.5) GOTO 51
      IF(LL.EQ.1.OR.LL.EQ.7) GOTO 51
      IF(LL.EQ.8) GOTO 51
      IF(ICAT.LE.4) GOTO 52
   51 IF(RNOX.LT.1000.) RNOX=1000.
   52 IF(ZO(LL).LE.0.001) GOTO 53
      C1=ALOG(CZ/ZO(LL))-SIC
      C1S2=C1+CKUSTA*RS2(LL,ICAT)+2.6
      C1O3=C1+CKUSTA*RO3(LL,ICAT)+2.4
      C1HNO3=C1+CKUSTA*10.+2.6
      C1NOX=C1+CKUSTA*RNOX+2.3
      GOTO 54
   53 CONTINUE
      ZCS2=DCS2/CKUSTA
      ZCO3=DCO3/CKUSTA
      ZCNOX=DCNOX/CKUSTA
```

```
      ZCHNO3=DCHNO3/CKUSTA
      C1S2=ALOG(CZ/ZCS2)+CKUSTA*RS2(LL,ICAT)-SIC
      C1O3=ALOG(CZ/ZCO3)+CKUSTA*RO3(LL,ICAT)-SIC
      C1NOX=ALOG(CZ/ZCNOX)+CKUSTA*RNOX-SIC
      C1HNO3=ALOG(CZ/ZCHNO3)-SIC
   54 VDS2(I,J)=VDS2(I,J)+CKUSTA*IUSE(LL)/C1S2
      VDO3(I,J)=VDO3(I,J)+CKUSTA*IUSE(LL)/C1O3
      VDNOX(I,J)=VDNOX(I,J)+CKUSTA*IUSE(LL)/C1NOX
      VDHNO3(I,J)=VDHNO3(I,J)+CKUSTA*IUSE(LL)/C1HNO3
      VDS4(I,J)=VDS4(I,J)+IUSE(LL)*CKUSTA/(ALOG(CZ/ZO(LL))
     1  +CKUSTA/CVDS-SIC)
   68 CONTINUE
C*** MULTIPLICATION BY 0.01 BECAUSE IUSE(LL) WAS IN %
      DO 70 J=1,LATOB
      DO 70 I=1,LONOB
      VDS2(I,J)=0.01*VDS2(I,J)
      VDO3(I,J)=0.01*VDO3(I,J)
      VDNOX(I,J)=0.01*VDNOX(I,J)
      VDHNO3(I,J)=0.01*VDHNO3(I,J)
   70 VDS4(I,J)=0.01*VDS4(I,J)
      PRINT 3100
 3100 FORMAT('0','SO2 DEPOSITION VELOCITY(M/S)')
      CALL OUTPUT(VDS2,LONOB,LATOB)
      PRINT 3200
 3200 FORMAT('0','SO4 DEPOSITION VELOCITY(M/S)')
      CALL OUTPUT(VDS4,LONOB,LATOB)
      PRINT 3300
 3300 FORMAT('0','O3 DEPOSITION VELOCITY(M/S)')
      CALL OUTPUT(VDO3,LONOB,LATOB)
      PRINT 3400
 3400 FORMAT('0','NOX DEPOSITION VELOCITY (M/S)')
      CALL OUTPUT(VDNOX,LONOB,LATOB)
      PRINT 3500
 3500 FORMAT('0','HNO3 DEPOSITION VELOCITY(M/S)')
      CALL OUTPUT(VDHNO3,LONOB,LATOB)
      REWIND 10
      REWIND 11
      REWIND 12
      RETURN
   99 PRINT 5000
 5000 FORMAT('0','*** END OF LANDUSE FILE ***')
      STOP
      END
      SUBROUTINE OUTPUT(VD,LONOB,LATOB)
C*********************************************
      DIMENSION VD(328,186)
      I3=LONOB/10
      DO 20 I4=1,I3,10
      I1=(I4-1)*10+1
      I2=I4*10
      IF(I2.GT.LONOB) GOTO 30
      PRINT 1000, I1,I2
 1000 FORMAT('0','I=',I3,' TO ',I3)
      DO 18 J=1,LATOB,10
```

```
   18 PRINT 2000, (VD(I,J),I=I1,I2)
 2000 FORMAT(' ',10E10.2)
   20 CONTINUE
   30 CONTINUE
      DO 44 J=1,LATOB,6
   44 WRITE(15,6000) (VD(I,J),I=1,LONOB,4)
 6000 FORMAT(7E10.3)
      RETURN
      END
//GO.SYSIN DD *
C*** #1 MIDSUMMER, MAX SURF SO4 DEP VEL(M/S;11F6.3), LANDTYPES 1-11
 0.001 0.01  0.01  0.01  0.01  0.001 0.01  0.01  0.01  0.01
C*** #2 AUTUM UNHARVESTED CROPLAND
 0.001 0.01  0.01  0.001 0.008 0.004 0.001 0.01  0.01  0.01  0.01
C*** #3 LATE AUTUMN AFTER FROST
 0.001 0.01  0.01  0.001 0.008 0.004 0.001 0.01  0.01  0.01  0.01
C*** #4 WINTER-SNOW ON GROUND
 0.001 0.01  0.01  0.001 0.008 0.004 0.001 0.01  0.01  0.01  0.01
C*** #5 TRANSITIONAL, SPRING & PARTIALLY GREEN
 0.001 0.01  0.01  0.01  0.01  0.01  0.001 0.01  0.01  0.01  0.01
C**********.**********.**********.**********.**********.**********.**********.**
C*** #1 MIDSUMMER, LUSH VEGETATION ZO(1.E-4 M; 11I6) FORTYPE 1-11
 30000  2500   500 10000 10000 10000     1    20  1500  1000  1000
C*** #2 AUTUMN WITH UNHARVESTED CROPLAND
 30000  1000   500 10000 10000 10000     1    20  1000   800   800
C*** #3 LATE AUTUMN AFTER FROST
 30000    50   500 10000 10000 10000     1    20  1000   200   600
C*** #4 WINTER-SNOW ON GROUND, SUBFREEZING
 30000    10    10 10000 10000 10000     1    20    10    10   400
C*** #5 TRANSITIONAL, SPRING & PARTIALLY GREEN SHORT ANNUALS
 30000   300   200 10000 10000 10000     1    20  1000   300   600
C*** SO2 SURFACE RESISTANCES (S/M) *******
C*** #1 MIDSUMMER, LUSH VEGETATION
A     500.   70.  100.   90.  150.   70.    0. 1000.   50.  100.  150.
B     500.   70.  100.   90.  150.   70.    0. 1000.   50.  100.  150.
C     500.  120.  140.  150.  240.  140.    0. 1000.   60.  140.  300.
D     500.  200.  200.  300.  400.  300.    0. 1000.   80.  200.  400.
E     500.  400.  400. 1200. 1200. 1000.    0. 1000.  100.  500.  500.
F      10.   10.   10.   50.   50.   50.    0.  500.   10.   10.   20.
C*** #2 AUTUMN WITH UNHARVESTED CROPLAND
A     500.  500.  400. 1000.  800.  600.    0. 1000.  100.  450.  500.
B     500.  500.  400. 1000.  800.  600.    0. 1000.  100.  450.  500.
C     500.  500.  400. 1000.  800.  600.    0. 1000.  100.  450.  500.
D     500.  500.  500. 1000.  800.  600.    0. 1000.  100.  500.  500.
E     500.  500.  500. 1000.  800.  600.    0. 1000.  100.  500.  500.
F      50.  100.  100.  100.  100.  100.    0.  500.   80.  100.  100.
C*** #3 LATE AUTUMN AFTER FROST
A     500.   50.  500. 1500. 1000.  600.    0. 1000.  100.  200.  500.
B     500.   50.  500. 1500. 1000.  600.    0. 1000.  100.  200.  500.
C     500.   50.  500. 1500. 1000.  600.    0. 1000.  100.  200.  500.
D     500.   50.  500. 1500. 1000.  600.    0. 1000.  100.  200.  500.
E     500.   50.  500. 1500. 1000.  600.    0. 1000.  100.  200.  500.
F      50.   50.  100.  100.  100.  100.    0.  500.   80.  100.  100.
C*** #4 WINTER, SNOW ON GROUND & SUBFREEZING
```

```
A    200.  100.  100. 1000.  500.  500.    0. 1000.  100.  100.  100.
B    200.  100.  100. 1000.  500.  500.    0. 1000.  100.  100.  100.
C    200.  100.  100. 1000.  500.  500.    0. 1000.  100.  100.  100.
D    200.  100.  100. 1000.  500.  500.    0. 1000.  100.  100.  100.
E    200.  100.  100. 1000.  500.  500.    0. 1000.  100.  100.  100.
F     50.  100.  100. 1000.  500.  500.    0.  500.  100.  100.  100.
C*** #5 TRANSITIONAL, SPRING & PARTIALLY GREEN SHORT ANNUALS
A    500.   50.  100.  250.  250.  100.    0. 1000.   50.   70.  300.
B    500.   50.  100.  250.  250.  100.    0. 1000.   50.   70.  300.
C    500.   60.  140.  350.  350.  200.    0. 1000.   60.  100.  400.
D    500.   90.  200.  500.  500.  400.    0. 1000.   80.  150.  500.
E    500.  300.  400. 1000. 1200. 1000.    0. 1000.  100.  350.  500.
F     10.   10.   10.   50.   50.   50.    0.  500.   10.   10.   20.
C*** O3 SURFACE RESISTANCES (S/M) *******
C*** #1 MIDSUMMER, LUSH VEGETATION
A    300.   60.   90.   80.  130.  100. 2000.  300.  150.   80.  120.
B    300.   60.   90.   80.  130.  100. 2000.  300.  150.   80.  120.
C    300.  100.  120.  130.  200.  200. 2000.  300.  200.  110.  200.
D    400.  150.  150.  170.  350.  400. 2000.  400.  300.  150.  300.
E    400.  250.  300. 1200. 1200. 1100. 2000.  400. 1000.  300.  300.
F    400.  400.  400. 1500. 1500. 1500. 2000.  400. 1200.  400.  400.
C*** #2 AUTUMN WITH UNHARVESTED CROPLAND
A    300.  200.  180.  200.  300.  300. 2000.  300.  200.  190.  200.
B    300.  200.  180.  200.  300.  300. 2000.  300.  200.  190.  200.
C    300.  200.  180.  200.  300.  300. 2000.  300.  200.  190.  200.
D    400.  200.  200.  600.  700.  700. 2000.  400.  350.  200.  300.
E    400.  200.  250. 1000. 1200. 1000. 2000.  400.  800.  220.  300.
F    400.  300.  300. 1500. 1500. 1500. 2000.  400. 1000.  300.  400.
C*** #3 LATE AUTUMN AFTER FROST SURFACE
A    300.  100.  200.  300.  300.  300. 2000.  300.  800.  150.  150.
B    300.  100.  200.  300.  300.  300. 2000.  300.  800.  150.  150.
C    300.  100.  200.  300.  300.  300. 2000.  300.  800.  150.  150.
D    400.  100.  200.  700.  800.  800. 2000.  400.  800.  150.  200.
E    400.  100.  200. 2000. 2000. 2000. 2000.  400.  800.  150.  300.
F    400.  200.  300. 2000. 2000. 2000. 2000.  400. 1000.  200.  400.
C*** #4 WINTER, SNOW ON GROUND & SUBFREEZING
A    500. 2000. 2000.  300.  300.  300. 2000.  300. 1000. 2000. 1000.
B    500. 2000. 2000.  300.  300.  300. 2000.  300. 1000. 2000. 1000.
C    500. 2000. 2000.  400.  400.  400. 2000.  300. 1000. 2000. 1000.
D    800. 2000. 2000.  800.  800.  800. 2000.  400. 1000. 2000. 1000.
E   1000. 2000. 2000. 2000. 2000. 2000. 2000.  400. 1000. 2000. 1000.
F   1000. 2000. 2000. 2000. 2000. 2000. 2000.  400. 1000. 2000. 1000.
C*** #5 TRANSITIONAL, SPRING & PARTIALLY GREEN SHORT ANNUALS
A    300.   40.   80.  200.  200.  150. 2000.  300.  400.   60.  100.
B    300.   40.   80.  200.  200.  150. 2000.  300.  400.   60.  100.
C    300.   50.  100.  300.  300.  200. 2000.  300.  400.   80.  150.
D    400.   80.  120.  400.  400.  400. 2000.  400.  500.  100.  250.
E    400.  200.  300. 1000. 1200. 1000. 2000.  400.  800.  250.  300.
F    400.  300.  400. 1500. 1500. 1500. 2000.  400. 1000.  350.  350.
//GO.FT10F001 DD DSN=NCC85,UNIT=READ6250,DISP=OLD,
//   DCB=(RECFM=FB,LRECL=80,BLKSIZE=8000,OPTCD=Q),
//   LABEL=(3,NL),VOL=SER=199846
//GO.FT15F001 DD DSN=B22882.VD.DATA,DISP=(NEW,CATLG),
//   UNIT=ALLTEMP,DCB=(LRECL=80,BLKSIZE=1680,RECFM=FB),
//   SPACE=(TRK,(50,5),RLSE)
```

APPENDIX 2 THE COMPUTER CODES OF A NCAR DRY DEPOSITION MODULE

```
      PROGRAM DEPTST
C
C *** This program is a dummy program which calls
C ***    the dry deposition routine (SUBROUTINE DRYDEP)
C
      REAL MOL
      PARAMETER (JMAX=1,LDUC=10,LSOLC=6,NUMSEA=5)
      PARAMETER (LTOTG=13)
C
      COMMON/POLNDX/LSO2,LSO4,LNO2,LNO,LO3,LHNO3,LH2O2,LALD,
     &  LHCHO,LOP,LPAA,LORA,LNH3
C
      COMMON/ADV/U(JMAX),V(JMAX)
      COMMON/M2DFC/T(JMAX),P(JMAX),QV(JMAX),Z(JMAX)
      COMMON/M1DFC/TGD(JMAX),UST(JMAX),Z0B(JMAX),Z0(JMAX,LDUC),
     2    MOL(JMAX),PBL(JMAX),XLUSE(JMAX,LDUC),Z01(JMAX,LDUC),
     3    UUSTC(JMAX),ICAT(JMAX),RADIAT(JMAX),PRECIP(JMAX)
C
      COMMON/C1DFC/VD(JMAX,LTOTG)
      COMMON/MTVR3D/VMKLAT,VMKLON
      COMMON/METTIM/JDSTRT,IHRSTRT
C
      DIMENSION IG(LTOTG)
C
      EQUIVALENCE (LSO2,IG(1))
C
      DO 13 I=1,LTOTG
      IG(I)=I
   13 CONTINUE
      READ(5,*) I1,J1,VMKLAT,VMKLON,(XLUSE(1,ILU),ILU=1,10)
      DO 14 ILU=1,10
   14 XLUSE(1,ILU)=XLUSE(1,ILU)*100.
      ISESN=5
      JDSTRT=112
      IHRSTRT=0
      WRITE(6,102) JDSTRT,IHRSTRT,ISESN,(XLUSE(1,ILU),ILU=1,10)
C
   20 CONTINUE
      READ(5,*,END=78) I1,J1,TIM,ZHT,UGRND,VGRND,QVGRND
C     READ(5,*,END=78) TGRND,TAIRG,RAIN
      READ(5,*,END=78) TGRND,TAIRG
      RAIN=0.
C
      TIMEC=TIM*3600.
      DO 330 J=1,JMAX
       TGD(J)=TGRND
       PRECIP(J)=RAIN
       U(J)=UGRND
       V(J)=VGRND
       QV(J)=QVGRND
       T(J)=TAIRG
       P(J)=100.
       PBL(J)=1500.
       Z(J)=ZHT
  330 CONTINUE
C
```

```
      CALL DRYDEP(ISESN,TIMEC)
C
      GOTO 20
   78 CONTINUE
      STOP
  102 FORMAT(' SIMULATION BEGINS ON JULIAN DATE',I5,', ',I3,' HR GMT',
     & /,' SEASON INDEX',I3,/,' LAND USE DISTRIBUTION= ',10F8.1)
      END
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCCCCCCCCCCCCCCC
      SUBROUTINE DRYDEP(ISESN,TIMEC)
C
      REAL MOL
      PARAMETER (JMAX=1,LDUC=10,LSOLC=6,NUMSEA=5)
      PARAMETER (LTOTG=6)
C
      COMMON/POLNDX/LSO2,LSO4,LNO2,LNO,LO3,LHNO3,LH2O2,LALD,
     &  LHCHO,LOP,LPAA,LORA,LNH3
C
      COMMON/ADV/U(JMAX),V(JMAX)
      COMMON/M2DFC/T(JMAX),P(JMAX),QV(JMAX),Z(JMAX)
C
      COMMON/M1DFC/TGD(JMAX),UST(JMAX),Z0B(JMAX),Z0(JMAX,LDUC),
     2    MOL(JMAX),PBL(JMAX),XLUSE(JMAX,LDUC),Z01(JMAX,LDUC),
     3    UUSTC(JMAX),ICAT(JMAX),RADIAT(JMAX),PRECIP(JMAX)
C
      COMMON/C1DFC/VD(JMAX,LTOTG)
      COMMON/MTVR3D/VMKLAT,VMKLON
      COMMON/METTIM/JDSTRT,IHRSTRT
C
      DIMENSION XNU(JMAX),WS(JMAX),RIB(JMAX),A5(JMAX),CKUSTA(JMAX),
     & RA(JMAX),RS0(JMAX),DTMP(JMAX),USTS(JMAX),RB(JMAX),RO0(JMAX)
C
      DIMENSION RS(LDUC,LSOLC,NUMSEA),VDSMAX(LDUC,NUMSEA),
     &  Z00(LDUC,NUMSEA),PDUM(JMAX,10),ZF(JMAX,10),UBAR(JMAX),
     &  RO(LDUC,LSOLC,NUMSEA)
C
      CHARACTER*15 LNAM(10),SNAM(5),POLN(9)
      DATA POLN/'Z0','U*','MOL','SO2','SO4','NO','NO2','O3','HNO3'/
C
      DATA LNAM/'URBAN','AGRICULTURE','RANGE','DEC FRST',
     &'CONF FRST','WET FRST','WATER','OTHER','SWAMP','AG/RANGE'/
C
      DATA SNAM/'SUMMER','EARLY ATM','LATE ATM','WINTER',
     &'SPRING'/
C
      DATA (VDSMAX(L,1),L=1,LDUC)
     1   /0.001,0.01,0.01, 0.01, 0.01, 0.01,0.001,0.01,0.01,0.01/
      DATA (VDSMAX(L,2),L=1,LDUC)
     1   /0.001,0.01,0.01,0.001,0.008,0.004,0.001,0.01,0.01,0.01/
      DATA (VDSMAX(L,3),L=1,LDUC)
     1   /0.001,0.01,0.01,0.001,0.008,0.004,0.001,0.01,0.01,0.01/
      DATA (VDSMAX(L,4),L=1,LDUC)
     1   /0.001,0.01,0.01,0.001,0.008,0.004,0.001,0.01,0.01,0.01/
      DATA (VDSMAX(L,5),L=1,LDUC)
     1   /0.001,0.01,0.01, 0.01, 0.01, 0.01,0.001,0.01,0.01,0.01/
```

```
C*****************************************
      DATA (Z00(L,1),L=1,LDUC)
     1   /3., .25, .05, 1., 1., 1., .0002, -9., .15, .10/
      DATA (Z00(L,2),L=1,LDUC)
     1   /3., .10, .05, 1., 1., 1., .0002, -9., .10, .08/
      DATA (Z00(L,3),L=1,LDUC)
     1   /3.,.005, .05, 1., 1., 1., .0002, -9., .10, .02/
      DATA (Z00(L,4),L=1,LDUC)
     1   /3.,.001,.001, 1., 1., 1., .0002, -9.,.001,.001/
      DATA (Z00(L,5),L=1,LDUC)
     1   /3., .03, .02, 1., 1., 1., .0002, -9., .10, .03/
C*************** Surface resistances SO2 & O3 *****************
C     SO2 Summer
      DATA (RS(L,1,1),L=1,LDUC)
     1 /500., 70., 100., 90., 150., 70., 0., 99., 50., 100./
      DATA (RS(L,2,1),L=1,LDUC)
     1 /500., 70., 100., 90., 150., 70., 0., 99., 50., 100./
      DATA (RS(L,3,1),L=1,LDUC)
     1 /500.,120., 140.,150., 240.,140., 0., 99., 60., 140./
      DATA (RS(L,4,1),L=1,LDUC)
     1 /500.,200., 200.,300., 400.,300., 0., 99., 80., 200./
      DATA (RS(L,5,1),L=1,LDUC)
     1 /500.,400., 400.,1200.,1200.,1000.,0.,99.,100., 500./
      DATA (RS(L,6,1),L=1,LDUC)
     1 / 10., 10.,  10.,  5.,  5.,  5.,0., 99.,10.,  10./
C     Ozone summer
      DATA (RO(L,1,1),L=1,LDUC)
     1   /300., 60., 90.,  80., 130., 100.,2000.,9999., 150., 80./
      DATA (RO(L,2,5),L=1,LDUC)
     1   /300., 60., 90.,  80., 130., 100.,2000.,9999., 150., 80./
      DATA (RO(L,3,5),L=1,LDUC)
     1   /300.,100.,120., 130., 200., 200.,2000.,9999., 200.,110./
      DATA (RO(L,4,5),L=1,LDUC)
     1   /400.,150.,150., 170., 350., 400.,2000.,9999., 300.,150./
      DATA (RO(L,5,5),L=1,LDUC)
     1   /400.,250.,300.,1200.,1200.,1100.,2000.,9999.,1000.,300./
      DATA (RO(L,6,5),L=1,LDUC)
     1   /400.,400.,400.,1500.,1500.,1500.,2000.,9999.,1200.,400./
C
C     SO2 Early fall
      DATA (RS(L,1,2),L=1,LDUC)
     1   /500.,500.,400.,1000.,800.,600.,0.,9999.,100.,450./
      DATA (RS(L,2,2),L=1,LDUC)
     1   /500.,500.,400.,1000.,800.,600.,0.,9999.,100.,450./
      DATA (RS(L,3,2),L=1,LDUC)
     1   /500.,500.,400.,1000.,800.,600.,0.,9999.,100.,450./
      DATA (RS(L,4,2),L=1,LDUC)
     1   /500.,500.,500.,1000.,800.,600.,0.,9999.,100.,500./
      DATA (RS(L,5,2),L=1,LDUC)
     1   /500.,500.,500.,1000.,800.,600.,0.,9999.,100.,500./
      DATA (RS(L,6,2),L=1,LDUC)
     1   / 50.,100.,100., 100.,100.,100.,0.,9999., 80.,100./
C     O3 Early fall
      DATA (RO(L,1,2),L=1,LDUC)
     1   /300.,200.,180., 200., 300., 300.,2000.,9999., 200.,190./
      DATA (RO(L,2,2),L=1,LDUC)
```

```
     1   /300.,200.,180., 200., 300., 300.,2000.,9999., 200.,190./
     DATA (RO(L,3,2),L=1,LDUC)
     1   /300.,200.,180., 200., 300., 300.,2000.,9999., 200.,190./
     DATA (RO(L,4,2),L=1,LDUC)
     1   /400.,200.,200., 600., 700., 700.,2000.,9999., 350.,200./
     DATA (RO(L,5,2),L=1,LDUC)
     1   /400.,200.,250.,1000.,1200.,1000.,2000.,9999., 800.,220./
     DATA (RO(L,6,2),L=1,LDUC)
     1   /400.,300.,300.,1500.,1500.,1500.,2000.,9999.,1000.,300./
C
C    SO2 Late fall
     DATA (RS(L,1,3),L=1,LDUC)
     1   /500.,50.,500.,1500.,1000.,600.,0.,9999.,100.,200./
     DATA (RS(L,2,3),L=1,LDUC)
     1   /500.,50.,500.,1500.,1000.,600.,0.,9999.,100.,200./
     DATA (RS(L,3,3),L=1,LDUC)
     1   /500.,50.,500.,1500.,1000.,600.,0.,9999.,100.,200./
     DATA (RS(L,4,3),L=1,LDUC)
     1   /500.,50.,500.,1500.,1000.,600.,0.,9999.,100.,200./
     DATA (RS(L,5,3),L=1,LDUC)
     1   /500.,50.,500.,1500.,1000.,600.,0.,9999.,100.,200./
     DATA (RS(L,6,3),L=1,LDUC)
     1   / 50.,50.,100., 100., 100.,100.,0.,9999., 80.,100./
C    O3 Late fall
     DATA (RO(L,1,3),L=1,LDUC)
     1   /300.,100.,200., 300., 300., 300.,2000.,9.,800.,150./
     DATA (RO(L,2,3),L=1,LDUC)
     1   /300.,100.,200., 300., 300., 300.,2000.,9.,800.,150./
     DATA (RO(L,3,3),L=1,LDUC)
     1   /300.,100.,200., 300., 300., 300.,2000.,9.,800.,150./
     DATA (RO(L,4,3),L=1,LDUC)
     1   /400.,100.,200., 700., 800., 800.,2000.,9.,800.,150./
     DATA (RO(L,5,3),L=1,LDUC)
     1   /400.,100.,200.,2000.,2000.,2000.,2000.,9.,800.,150./
     DATA (RO(L,6,3),L=1,LDUC)
     1   /400.,200.,300.,2000.,2000.,2000.,2000.,9.,1000.,200./
C
C    SO2 Winter
     DATA (RS(L,1,4),L=1,LDUC)
     1   /200.,100.,100.,1000.,500.,500.,0.,9999.,100.,100./
     DATA (RS(L,2,4),L=1,LDUC)
     1   /200.,100.,100.,1000.,500.,500.,0.,9999.,100.,100./
     DATA (RS(L,3,4),L=1,LDUC)
     1   /200.,100.,100.,1000.,500.,500.,0.,9999.,100.,100./
     DATA (RS(L,4,4),L=1,LDUC)
     1   /200.,100.,100.,1000.,500.,500.,0.,9999.,100.,100./
     DATA (RS(L,5,4),L=1,LDUC)
     1   /200.,100.,100.,1000.,500.,500.,0.,9999.,100.,100./
     DATA (RS(L,6,4),L=1,LDUC)
     1   / 50.,100.,100.,1000.,500.,500.,0.,9999.,100.,100./
C    O3 Winter
     DATA (RO(L,1,4),L=1,LDUC)
     1   / 500.,2000.,2000., 300., 300., 300.,2000.,9.,1000.,2000./
     DATA (RO(L,2,4),L=1,LDUC)
     1   / 500.,2000.,2000., 300., 300., 300.,2000.,9.,1000.,2000./
     DATA (RO(L,3,4),L=1,LDUC)
```

```
     1   / 500.,2000.,2000., 400., 400., 400.,2000.,9.,1000.,2000./
      DATA (RO(L,4,4),L=1,LDUC)
     1   / 800.,2000.,2000., 800., 800., 800.,2000.,9.,1000.,2000./
      DATA (RO(L,5,4),L=1,LDUC)
     1   /1000.,2000.,2000.,2000.,2000.,2000.,2000.,9.,1000.,2000./
      DATA (RO(L,6,4),L=1,LDUC)
     1   /1000.,2000.,2000.,2000.,2000.,2000.,2000.,9.,1000.,2000./
C
C     SO2 Spring
      DATA (RS(L,1,5),L=1,LDUC)
     1   /500., 50.,100., 100., 250., 100.,0.,9999., 50.,70./
      DATA (RS(L,2,5),L=1,LDUC)
     1   /500., 50.,100., 100., 250., 100.,0.,9999., 50.,70./
      DATA (RS(L,3,5),L=1,LDUC)
     1   /500., 60.,140., 350., 350., 200.,0.,9999., 60.,100./
      DATA (RS(L,4,5),L=1,LDUC)
     1   /500., 90.,200., 500., 500., 400.,0.,9999., 80.,150./
      DATA (RS(L,5,5),L=1,LDUC)
     1   /500.,300.,400.,1000.,1200.,1000.,0.,9999.,100.,350./
      DATA (RS(L,6,5),L=1,LDUC)
     1   / 10., 10., 10.,  50.,  50.,  50.,0.,9999., 10., 10./
C     O3 Spring
      DATA (RO(L,1,5),L=1,LDUC)
     1   /300., 40., 80., 200., 200., 150.,2000.,9., 400., 60./
      DATA (RO(L,2,5),L=1,LDUC)
     1   /300., 40., 80., 200., 200., 150.,2000.,9., 400., 60./
      DATA (RO(L,3,5),L=1,LDUC)
     1   /300., 50.,100., 300., 300., 200.,2000.,9., 400., 80./
      DATA (RO(L,4,5),L=1,LDUC)
     1   /400., 80.,120., 400., 400., 400.,2000.,9., 500.,100./
      DATA (RO(L,5,5),L=1,LDUC)
     1   /400.,200.,300.,1000.,1200.,1000.,2000.,9., 800.,250./
      DATA (RO(L,6,5),L=1,LDUC)
     1   /400.,300.,400.,1500.,1500.,1500.,2000.,9.,1000.,350./
C
C                         INDICES USED
C       Land                                                  Season
                                                              Insolation
C     1 URBAN LAND                                          1 SUMMER
                                                            1 >400 WATTS/M2
C     2 AGRICULTURE                                         2 EARLY FALL
                                                            2 >400 WATTS/M2
C     3 RANGE
                                                            3 LATE FALL
                                                            3 200 - 400
C     4 DECIDUOUS FOREST                                    4 WINTER
                                                            4 0-200
C     5 CONIFEROUS FOREST                                   5 SPRING
                                                            5 NIGHT
C     6 MIXED FOREST WETLAND
```

```
                                                                  6 WETTED
C    7 WATER
C    8 OTHER
C    9 NON-FORESTED WETLAND
C   10 MIXED AGRICULTURE/RANGELAND
C
     RHO0=1.225E-3
     CPAIR=.24
     H20MW=18.016
     AIRMW=28.9644
     TOG=273.15/9.81
     TOGK=TOG/.4
     GAMMA=9.8E-3
     CON1=1.E-9*101.325/(RHO0*273.15*CPAIR)
     CON2=1.E-8*101.325/(273.15*RHO0)
     CON3=.16*9.4
     CON4=.16/.74
     ANGRAD=3.141592654/180.
     ANG1=ANGRAD*90./91.3125
C
     DO 200 J=1,JMAX
C
     PDUM(J,1)=T(J)-273.15
C
C  VISCOSITY OF AIR (Used in scaling water surface roughness height)
     XNU(J)=T(J)*(1.718+.0049*PDUM(J,1))/P(J)*CON2
C
C  MIXING RATIO OF WATER AT GROUND (ASSUMED SATURATED)
     PDUM(J,6)=QSAT(TGD(J),P(J))
C
C  COMPUTE VIRTUAL TEMPERATURE OF GROUND AND AIR ABOVE GROUND
C
     PDUM(J,2)=TGD(J)*(1.+.6077*PDUM(J,6))
     PDUM(J,3)=T(J)*(1.+.6077*QV(J))
     DTMP(J)=PDUM(J,3)-PDUM(J,2)+Z(J)*GAMMA
     DTMP(J)=CVMGZ(1.E-20,DTMP(J),DTMP(J))
C
C  COMPUTE SCALAR WIND SPEED WS
     PDUM(J,4)=U(J)
     PDUM(J,5)=V(J)
     WS(J)=AMAX1(PDUM(J,4)*PDUM(J,4)+PDUM(J,5)*PDUM(J,5),1.E-10)
C
C  COMPUTE RICHARDSON NUMBER
     RIB(J)=Z(J)*DTMP(J)/(TOG*WS(J))
     RIB(J)=CVMGZ(1.E-20,RIB(J),RIB(J))
     WS(J)=SQRT(WS(J))
     A5(J)=(1.+4.7*RIB(J))
     A5(J)=1./CVMGZ(1.E-20,A5(J),A5(J))
  200 CONTINUE
C
     DO 201 J=1,JMAX
C  *** DETERMINE INSOLATION AT GIVEN GRID POINT FROM SOLAR ANGLE
FORMULA
C
C       LOCAL HOUR ANGLE
     PDUM(J,1)=(TIMEC/3600.+IHRSTRT-VMKLON/15.-12.)*15.*ANGRAD
```

```
C
C      INCLINATION ANGLE
      PDUM(J,2)=ANGRAD*23.5*SIN((JDSTRT+TIMEC/86400.-81.1875)*ANG1)
C
C      LATITUDE ANGLE (RAD)
      PDUM(J,3)=ANGRAD*VMKLAT
C
C *** RADIATION CALCULATION
C
      RADIAT(J)=1000.*(SIN(PDUM(J,3))*SIN(PDUM(J,2))+
     &     COS(PDUM(J,3))*COS(PDUM(J,2))*COS(PDUM(J,1)))
C
C*** CLASSIFICATION OF SURFACE RESISTANCES ACCORDING TO SOLAR
C   RADIATION R (W/M**2) FOR INSOLATION CATEGORIES (1,2) R>400,
C   (3) 400>R>200, (4) 200>R>1, (5) R=0 AND WS>1 M/S,
C   (6) SURFACE WETNESS PRESENT (RAIN OR DEW)
C
      CAT=1.
      CAT=CVMGP(CAT,3.,RADIAT(J)-400.)
      CAT=CVMGP(CAT,4.,RADIAT(J)-200.)
      CAT=CVMGP(CAT,5.,RADIAT(J)-1.)
C
C  Compute if ground temperature is cooler than dew point of air above
C          and test to see if rainfall has wetted surface
      EMAX=QV(J)*P(J)/(.622+QV(J))
      DEWPT=5417.4/(19.83-ALOG(EMAX/.611))
      IF(TGD(J).LT.DEWPT) CAT=6.
      IF(PRECIP(J).GT.0.01) CAT=6.
      ICAT(J)=CAT+.5
C
  201 CONTINUE
C
C  INITIALIZE ALL DEPOSITION VELOCITIES TO ZERO
      DO 443 J=1,JMAX
      DO 443 JDUM=1,LTOTG
  443 VD(J,JDUM)=0.
C
C SET UP INITIAL LAND USE ARRAY OF Z0 (WATER SFCS WILL UPDATE THESE
#'S)
      DO 355 ILU=1,LDUC
      IF(ILU.EQ.8) GOTO 355
      DO 355 J=1,JMAX
      Z0(J,ILU)=Z00(ILU,ISESN)
  355 CONTINUE
C
C  COMPUTE THE AVERAGE SURFACE ROUGHNESS HEIGHT FOR EACH GRID
SQUARE
C  INITIALIZE AVERAGE AND LAND USE ROUGHNESS HEIGHTS
C
      NWAT=4
      DO 377 IX=1,NWAT
      DO 351 J=1,JMAX
      Z0B(J)=0.
 351   CONTINUE
C
      DO 354 ILU=1,LDUC
```

```
      IF(ILU.EQ.8) GOTO 354
      DO 354 J=1,JMAX
      Z0B(J)=LOG(Z0(J,ILU))*XLUSE(J,ILU)/100.+Z0B(J)
  354 CONTINUE
      DO 202 J=1,JMAX
      Z0B(J)=EXP(Z0B(J))
C
C  CALCULATE FRICTION VELOCITY (U*) BY LOUIS FORMULA
      PDUM(J,1)=ALOG(Z(J)/Z0B(J))
      PDUM(J,2)=.4*WS(J)/PDUM(J,1)
      PDUM(J,3)=CON3/PDUM(J,1)/PDUM(J,1)*SQRT(ABS(RIB(J))*
     &    (Z(J)/Z0B(J)))
      PDUM(J,4)=CON4*WS(J)*DTMP(J)/(PDUM(J,1)*PDUM(J,1))
C
C  COMPUTE UU* FOR GRID AVERAGE
      PDUM(J,9)=1.+7.4*PDUM(J,3)
      UST(J)=CVMGP(A5(J),
     &  SQRT(ABS(1.-9.4*RIB(J)/PDUM(J,9)))
     1  ,RIB(J))
      UST(J)=AMAX1(PDUM(J,2)*UST(J),1.E-10)
      UUSTC(J)=UST(J)*WS(J)
  202 CONTINUE
C
      DO 302 J=1,JMAX
C
C *** Ocean/water roughness computed from grid-averaged friction velocity
      Z0(J,7)=.014*UST(J)*UST(J)/9.81 + XNU(J)/(9.1*UST(J))
      UBAR(J)=0.
  302 CONTINUE
  377 CONTINUE
C
C  BEGIN LOOP TO CALCULATE DEPOSITION VELOCITY OVER ALL LAND TYPES
C
      TIM=TIMEC/3600.
      WRITE(6,98) Z(1), T(1), DEWPT, TGD(1)
      WRITE(6,99) TIM
      WRITE(6,100) SNAM(ISESN),RADIAT(1),DTMP(1),WS(1),RIB(1),
     & Z0B(1),UUSTC(1),ICAT,POLN
      DO 444 ILU=1,LDUC
      IWAT=1
      IF(ILU.EQ.8) GOTO 444
      IF(ILU.EQ.7) IWAT=4
      DO 378 IW=1,IWAT
C
C AERODYNAMIC RESISTANCE ARRAY --- SAME TERMS FOR ALL DEPOSITION
CALC'S
      DO 353 J=1,JMAX
      PDUM(J,1)=ALOG(Z(J)/Z0(J,ILU))
      PDUM(J,2)=.4*UUSTC(J)/PDUM(J,1)
      PDUM(J,3)=CON3/PDUM(J,1)/PDUM(J,1)*SQRT(ABS(RIB(J))*
     &    (Z(J)/Z0(J,ILU)))
C
C  COMPUTE W'T' AND U* FOR STABLE OR UNSTABLE CONDITIONS
      PDUM(J,9)=1.+7.4*PDUM(J,3)
      UST(J)=CVMGP(A5(J),SQRT(ABS(1.-9.4*RIB(J)/PDUM(J,9))),RIB(J))
      UST(J)=AMAX1(SQRT(PDUM(J,2)*UST(J)),1.E-10)
```

```
      X1=PDUM(J,1)+2.
      IF(ILU.EQ.7) X1=PDUM(J,1)
      PDUM(J,4)=CON4*UUSTC(J)*DTMP(J)/(UST(J)*PDUM(J,1)*X1)
      USTS(J)=CVMGP(PDUM(J,4)*A5(J)*A5(J),
     &       PDUM(J,4)*(1.-9.4*RIB(J)/(1.+5.3*PDUM(J,3))),RIB(J))
      USTS(J)=CVMGZ(1.E-20,USTS(J),USTS(J))
C
C  COMPUTE MONIN-OBUKHOV LENGTH SALE
      MOL(J)=TOGK*UST(J)*UST(J)*UST(J)/(USTS(J))
      MOL(J)=CVMGZ(1.E-20,MOL(J),MOL(J))
C
C  Determine stable and unstable stability correction functions
C
      PDUM(J,5)=Z(J)/MOL(J)
      PDUM(J,7)=ALOG(ABS(AMAX1(PDUM(J,5),-1.)))
      PDUM(J,6)=CVMGP(-5.*AMIN1(PDUM(J,5),.99),
     &        EXP(0.598+0.39*PDUM(J,7)-0.09*PDUM(J,7)*PDUM(J,7)),
     &        PDUM(J,5))
C
      CKUSTA(J)=0.4*UST(J)
      RB(J)=2.83/CKUSTA(J)
      RA(J)=(ALOG(Z(J)/Z0(J,ILU))-PDUM(J,6))/CKUSTA(J)
      IF(ILU.EQ.7) Z0(J,7)=.032*UST(J)*UST(J)/9.81+.0001
  353 CONTINUE
  378 CONTINUE
      UBAR(1)=UBAR(1)+UUSTC(1)/UST(1)*XLUSE(1,ILU)/100.
C
C SET UP SURFACE RESISTANCE ARRAY
      DO 199 J=1,JMAX
      II1=ICAT(J)
      RS0(J)=RS(ILU,II1,ISESN)
      RO0(J)=RO(ILU,II1,ISESN)
      PDUM(J,4)=1.
C
C  TEST TO SEE IF STABLE PBL HEIGHT IS SMALLER THAN DZ IN LOWEST
LAYER
      IF(MOL(J).GE.0.) THEN
          PBLS=.4*SQRT(UST(J)*MOL(J)/1.E-4)
          PDUM(J,4)=AMIN1(PBLS/(2.*Z(J)),1.)
      END IF
C
  199 CONTINUE
C
C********************* DEPOSITION OF SO2
C
      DO 203 J=1,JMAX
C       SO2 GAS DIFFUSION IN AIR
      PDUM(J,2)=.116E-4/P(J)*100.*(T(J)/273.15)**1.75
      ZF(J,5)=PDUM(J,2)/CKUSTA(J)
      PDUM(J,3)=CVMGP(RA(J)+RB(J),
     &        (ALOG(Z(J)/ZF(J,5))-PDUM(J,6))/CKUSTA(J),
     &        Z0(J,ILU)-.001)
C Surface resistance
        VSO2=PDUM(J,4)/(PDUM(J,3)+RS0(J))*100.
        VD(J,LSO2)=VD(J,LSO2)+XLUSE(J,ILU)*VSO2/100.
  203 CONTINUE
```

```
C
C********************** DEPOSITION OF SO4
C
      DO 204 J=1,JMAX
C       SCALE MAXIMUM DEPOSITION VELOCITY ACCORDING TO STABILITY
        PDUM(J,1)=CVMGP(1.,
     &       (1.+(ABS(-300./MOL(J)))**0.6667),
     &         MOL(J))
        PDUM(J,1)=CVMGP(.002*PDUM(J,1),
     &    0.0009*(ABS(-PBL(J)/MOL(J)))**0.6667 ,
     &    PBL(J)/MOL(J)+30.)
C*** SET VDS TO BE LESS THAN VDSMAX
      PDUM(J,1)=AMIN1(VDSMAX(ILU,ISESN),UST(J)*PDUM(J,1))
      VSO4=PDUM(J,4)/(RA(J)+1./PDUM(J,1))*100.
      VD(J,LSO4)=VD(J,LSO4)+XLUSE(J,ILU)*VSO4/100.
C
  204 CONTINUE
C
C********************** DEPOSITION OF NO2
C
      DO 205 J=1,JMAX
        VNO2=PDUM(J,4)*100./(RA(J)+RB(J)+CVMGZ(500.,RS0(J),RS0(J)))
        VD(J,LNO2)=VD(J,LNO2)+XLUSE(J,ILU)*VNO2/100.
  205 CONTINUE
C
C ********************** DEPOSITION OF NO
C
      DO 206 J=1,JMAX
        VNO=PDUM(J,4)*100./(RA(J)+RB(J)+CVMGZ(500.,RS0(J),RS0(J)))
        VD(J,LNO)=VD(J,LNO)+XLUSE(J,ILU)*VNO/100.
  206 CONTINUE
C
C ********************** DEPOSITION OF O3
C
      DO 207 J=1,JMAX
        VO3=PDUM(J,4)*100./(RA(J)+RB(J)+RO0(J))
        VD(J,LO3)=VD(J,LO3)+XLUSE(J,ILU)*VO3/100.
  207 CONTINUE
C
C ********************** DEPOSITION OF HNO3
C
      DO 208 J=1,JMAX
        VHNO3=PDUM(J,4)*100./(RA(J)+RB(J))
        VD(J,LHNO3)=VD(J,LHNO3)+XLUSE(J,ILU)*VHNO3/100.
C
  208 CONTINUE
C ********************** DEPOSITION OF H2O2
C
      DO 209 J=1,JMAX
        VD(J,LH2O2)=VD(J,LH2O2)+XLUSE(J,ILU)*PDUM(J,4)/
     &              (RA(J)+RB(J)+.1*RS0(J))
  209 CONTINUE
C ********************** DEPOSITION OF ALD
C
      DO 210 J=1,JMAX
        VD(J,LALD)=VD(J,LALD)+XLUSE(J,ILU)*PDUM(J,4)/
```

```
     &            (RA(J)+RB(J)+2.*RS0(J))
  210 CONTINUE
C ********************* DEPOSITION OF HCHO
C
      DO 211 J=1,JMAX
        VD(J,LHCHO)=VD(J,LHCHO)+XLUSE(J,ILU)*PDUM(J,4)/
     &            (RA(J)+RB(J)+.5*RS0(J))
  211 CONTINUE
C ********************* DEPOSITION OF OP
C
      DO 212 J=1,JMAX
        VD(J,LOP)=VD(J,LOP)+XLUSE(J,ILU)*PDUM(J,4)/
     &            (RA(J)+RB(J)+.3*RS0(J))
  212 CONTINUE
C ********************* DEPOSITION OF PAA
C
      DO 213 J=1,JMAX
        VD(J,LPAA)=VD(J,LPAA)+XLUSE(J,ILU)*PDUM(J,4)/
     &            (RA(J)+RB(J)+.3*RS0(J))
  213 CONTINUE
C ********************* DEPOSITION OF ORA
C
      DO 214 J=1,JMAX
        VD(J,LORA)=VD(J,LORA)+XLUSE(J,ILU)*PDUM(J,4)/
     &            (RA(J)+RB(J)+RS0(J))
  214 CONTINUE
C ********************* DEPOSITION OF NH3
C
      DO 215 J=1,JMAX
        VD(J,LNH3)=VD(J,LNH3)+XLUSE(J,ILU)*PDUM(J,4)/
     &            (RA(J)+RB(J)+.2*RS0(J))
  215 CONTINUE
C
      WRITE(6,101) LNAM(ILU),Z0(1,ILU),UST(1),MOL(1),VSO2,VSO4,VNO,
     &  VNO2,VO3,VHNO3
  444 CONTINUE
      WRITE(6,103) UBAR(1),(VD(1,I),I=1,6)
C     WRITE(6,103) (VD(1,I),I=1,6)
C
      RETURN
   98 FORMAT(' ',//,' ',T15,'DEPOSITION VELOCITY ANALYSIS (CM/S) AT',
     &' HEIGHT =',F8.2,' M  AIR, DEW POINT, GROUND T(K)=',3F8.2)
   99 FORMAT(' ','TIME=',F5.2,T15,'RADIATION (W/M2)',T38,
     &'DTEMP (K)',T50,'WIND SPEED (M/S)',T70,'RICHARDSON #',
     &'  ZOB(M)   U.U*(M2/S2)  ICAT')
  100 FORMAT(' ',A11,3F15.2,5X,E15.4,1P2E12.4,I3,/' ',18X,9A12)
  101 FORMAT(' ',A11,9G12.4)
C 103 FORMAT(' AVERAGE DEPOSITION VELOCITY=',19X,6G12.4)
  103 FORMAT(' AVG WIND SPEED=',F14.2,' M/S  AVG DEP VEL=',6G12.4)
      END
CCCC
```

```
      PMB=PCB*10.
      H20MW=18.016
      AIRMW=28.9644
      TC=TK-273.15
C  Polynomial fit in Pruppacher(1978) for sat vapor pressure(mb)
      A0=6.107788861
      A1=.4436518521
      A2=1.428945805E-2
      A3=2.650648471E-4
      A4=3.031240396E-6
      A5=2.034080948E-8
      A6=6.136820929E-11
C SATURATION VAPOR PRESSURE (MB) OVER WATER (VALID -50 TO +50 C)
      ESAT=A0+TC*(A1+TC*(A2+TC*(A3+TC*(A4+TC*(A5+A6*TC)))))
C Actual molecular weight of moist air
      AMW=ESAT/PMB*H20MW+(1.-ESAT/PMB)*AIRMW
      QSAT=ESAT*H20MW/AMW/PMB
      RETURN
      END
C
C ***    THIS FUNCTION ACTS LIKE THE CRAY FUNCTION  CVMGP   ****
C
      FUNCTION CVMGP(X1,X2,X3)
      IF(X3) 10,20,20
   10 CVMGP=X2
      RETURN
   20 CVMGP=X1
      RETURN
      END
C
C ***    THIS FUNCTION ACTS LIKE THE CRAY FUNCTION CVMGZ ****
C
      FUNCTION CVMGZ(X1,X2,X3)
      CVMGZ=X2
      IF(ABS(X3).LT.1.E-20) CVMGZ=X1
      RETURN
      END
```